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Impacts of urban development and climate change in exposing cities to pluvial flooding

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PhD Thesis
April 2016

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Preface

The research presented in this PhD thesis was carried out at the Department of Management Engineering at the Technical University of Denmark (DTU) and was supervised by Senior Researcher Martin Drews (DTU Management), Professor Karsten Arnbjerg-Nielsen (DTU Environment) and Professor Henrik Madsen (DHI). The PhD project was funded by the Department of Management Engineering and completed in the period December 2012 to April 2016.

The PhD project takes the form of a paper-based thesis produced in accordance with the guidelines of the Technical University of Denmark. It consists of an extended summary followed by six scientific publications (see below). The summary introduces the research area and highlights and discusses the main findings of the scientific publications.

- I. **Kaspersen, P.**, Fensholt, R., Drews, M. 2015. Using Landsat Vegetation Indices to Estimate Impervious Surface Fractions for European Cities. *Remote Sensing* 7, 8224–8249. doi:10.3390/rs70608224
- II. **Skougaard Kaspersen, P.**, Høegh Ravn, N., Arnbjerg-Nielsen, K., Madsen, H., Drews, M. 2015. Influence of urban land cover changes and climate change for the exposure of European cities to flooding during high-intensity precipitation. *Proceedings of the International Association of Hydrological Sciences (PIAHS)*, Volume 370, 21–27. doi:10.5194/piahs-370-21-2015
- III. **Skougaard Kaspersen, P.**, Høegh Ravn, N., Arnbjerg-Nielsen, K., Madsen, H., Drews, M. Comparison of the impacts of urban development and climate change for the exposure of European cities to pluvial flooding, Manuscript in preparation for *Hydrology and Earth System Sciences (HESS)*. (To be submitted May 2016).
- IV. Halsnæs, K., **Kaspersen, P.**, Drews, M. 2015. Key drivers and economic consequences of high-end climate scenarios: uncertainties and risks. *Climate Research*. 64, 85–98. doi:10.3354/cr01308
- V. **Skougaard Kaspersen, P.**, Halsnæs, K. Integrated climate change risk assessment for localized extreme precipitation, *Environmental Management*, Springer, in review.
- VI. Halsnæs, K., **Kaspersen, P.S.**, Trærup, S. 2016. Climate Change Risks – Methodological Framework and Case Study of Damages from Extreme Events in Cambodia, in: Uitto, J.I., Shaw, R. (Eds.), *Sustainable Development and Disaster Risk Reduction*. Springer Japan, Tokyo, pp. 71–85.

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Finally the biggest gratitude goes to Julie and Magne for clearing my head by keeping me occupied elsewhere during the hours where I was not working on my PhD, and for allowing me to work extra during the weekends and evenings when it was needed.

Summary

Urban areas are characterized by very high concentrations of people and economic activities and are thus particularly vulnerable to flooding during extreme precipitation. Urban development and climate change are among the key drivers of changes in the exposure of cities to the occurrence and impacts of pluvial flooding. Cities are often dominated by large areas of impervious surfaces, that is, man-made sealed surfaces which water cannot penetrate, and increases in these – for example, as a consequence of urban development – can cause elevated run-off volumes and flood levels during precipitation. Climate change is expected to affect the intensity and frequency of extreme precipitation, with increases projected for many regions, including most parts of Europe.

The main objective of this thesis is to improve our understanding of the dual importance of urban development and climate change in exposing cities to pluvial flooding. Increased knowledge of these phenomena will enable local and national decision-makers to prioritize efficiently between different adaptation measures and mitigation strategies when planning the climate-proofing of cities in the future.

The high complexity of urban environments, where many different land use and cover types are present within short distances, poses a challenge for mapping at finer scales. For many applications, satellite-based remote-sensing techniques provide superior coverage of urban areas and facilitate the systematic, accurate and resource-efficient mapping of urban land cover and changes to it over time. Since many European cities are almost exclusively characterized by a combination of impervious surfaces and green vegetation, information on vegetation cover from remote sensors can be utilized to provide estimates of the quantity and spatial distribution of impervious surfaces. In this work for example vegetation cover, as measured using Landsat satellite imagery, is found to provide accurate estimates of subpixel imperviousness for eight European cities. Furthermore, as only minor variations in the accuracies are observed for the examined cities, this suggests that the method can be applied with similar accuracies for urban areas in other geographical locations, both within and outside of Europe. The Soil Adjusted Vegetation Index (SAVI) is identified as a superior index for mapping multiple cities within a larger geographical area using regional regression models, and in most cases we find that the quantification models based on Landsat imagery are readily transferable in space, with only a limited loss of precision.

The impacts of recent historical urban development and anticipated future climate change on exposure to pluvial flooding are investigated for four European cities – Nice, Strasbourg, Vienna and Odense – to represent the diversity of flood regimes, urban morphologies, urban development patterns and hydrological responses that exists across the European continent. The analyses of changes to the urban land cover show that the four cities all experienced increased levels of imperviousness between 1984 and 2015, with absolute changes ranging from 7% to 12%. We find that this increase is driven primarily by cities expanding into former non-urban areas and only marginally due to intensifications of existing urban land cover. The influence of urban development on flood exposure shows a clear trend towards the greater impact of soil sealing for the least severe precipitation events, while only marginally affecting flooding during more extreme precipitation. Changes to urban land cover are found to have a particular influence on flood exposure in urban areas characterized by coarser soil textures and limited elevation differences, as soil infiltration rates are excessive in these cases, increasing the impacts of soil sealing. Urban development in 1984-2015 caused flooding to increase by 0-5% every time overall imperviousness increased by 1%, while affecting flooding with higher water levels the most. Climate change impacts on precipitation extremes are projected for RCP (Representative Concentration Pathway) 4.5 and RCP 8.5 based on extreme value analysis using a change factor (CF) methodology. The estimated changes in the intensity and frequency of extreme precipitation are identified as highly uncertain, but with average CFs projecting an increase in precipitation intensities and flooding extents for all four cities. The projected trends in extremes show a positive correlation with increasing return periods and increasing concentrations of atmospheric greenhouse gasses. Hence the largest increases are projected for the most extreme

events under high-end climate scenarios, such as RCP 8.5. For Odense and Vienna, the impacts of climate change on flood exposure under the RCP 4.5 scenario is in the same order of magnitude as that caused by urban development, while in all cases we find the expected changes in precipitation intensities under the RCP 8.5 scenario to affect flooding the most. In the context of climate adaptation, the findings suggest that the efficiency of "green" adaptation measures, that is, where natural infiltration and the storage of surface water are used as a measure to reduce exposure to flooding – differs substantially between locations, being an efficient strategy against pluvial flooding for some cities, while being only marginally effective for others.

Analyses of the consequences of high-end climate scenarios and the risks of extreme precipitation involve a number of critical assumptions and methodological challenges related to key uncertainties in climate scenarios and modelling, impact analysis, and economics. A methodological framework for the integrated risk assessment of climate change impacts has been developed and applied to a case study of pluvial flooding in the city of Odense, Denmark. It addresses the complex linkages between the different kinds of data required in a climate adaptation context, emphasizing that the availability of spatially explicit data reduces the overall uncertainty of the risk assessment and can assist in highlighting key vulnerable assets in a decision-making context. Also, using an integrated framework enables the identification of the relative importance of the different factors (i.e. degree of climate change, assets value, discount rate etc.) that influence the overall output of the assessment. A sensitivity analysis examines 32 combinations of climate scenarios, damage cost methods and economic variables, demonstrating that alternative assumptions result in risk estimates with a very large variation. We find that a major source of uncertainty relates to the climate scenario of choice, in particular the probability of extreme events and the economic assumptions made, including choices of risk aversion factor and discount rate. Moving from our current climate to higher atmospheric greenhouse gas (GHG) concentrations implies that the frequency of extreme events increases. In combination with various economic assumptions, we find that the annualized damage costs for the lowest and highest estimates vary from about 85 million EUR yr⁻¹ down to less than 1 million EUR yr⁻¹. In terms of decision-making, however, it is important to note that most of the combinations assess the risk to be between 7 and 30 million EUR yr⁻¹, while only 4 out of the 32 combinations really stand out and go far beyond a 30 million EUR yr⁻¹ risk level. The level of risk is found to vary in nearly equal parts based on climate scenario assumptions, damage cost approach and cost assumptions, and we observe that the set of climate scenarios and economic assumptions influences the risk estimates in a very similar way. Consequently, this study demonstrates that, in terms of decision-making, the actual expectations concerning future climate scenarios and the economic assumptions applied are very important in determining the risks of extreme climate events and, accordingly, the level of cost-effective adaptation seen from the society's point of view.

Least developed countries (LDCs) are particularly vulnerable to climate change due to their low incomes, weak infrastructure and limited institutional capacity for coping with climate change. Extreme events occurring in recent decades point to the threat of increasing frequencies and damages in the future. Despite uncertainties about whether such events should be attributed to climate change, it is important to strengthen data and methodological frameworks further in order to assess the risks in highly vulnerable low income countries. We suggest applying specific assumptions to willingness to pay (WTP) estimates for avoided damage to LDCs reflecting risk aversion and equity concerns using an inequality aversion factor, which gives relatively high weight to damage and therefore the income losses of poor households. It is demonstrated that the application of an inequality factor strongly influences WTP estimates for avoided damages and we find a factor of ten between the highest and lowest estimates. This suggests that including such assumptions are very important, seen in the context of economic arguments for investing in adaptation in LDC's.

Dansk sammenfatning

Byer er kendetegnet ved meget høje koncentrationer af mennesker og økonomiske aktiviteter, hvilket gør dem særligt sårbare overfor oversvømmelser i forbindelse med ekstrem nedbør. Byudvikling og klimaforandringer er blandt de vigtigste drivkræfter for ændringer i byers sårbarhed overfor forekomsten og konsekvenserne af oversvømmelser i forbindelse med skybrud. Bymiljøer er ofte domineret af store områder med befæstede overflader, dvs. menneskeskabte forseglede overflader, som vand ikke kan trænge igennem, og stigninger i disse - for eksempel som følge af byudvikling - kan medføre forhøjet overfladeafstrømning og øget risiko for oversvømmelser. Fremtidige klimaændringer forventes at påvirke intensiteten og hyppigheden af ekstrem nedbør, med projekterede stigninger for mange regioner, herunder for store dele af Europa.

Hovedformålet med denne afhandling er at øge vores viden om betydningen af byudvikling og klimaændringer for oversvømmelser i byer i forbindelse med skybrud. Øget viden om disse sammenhænge bidrager med information som er nødvendig for lokale og nationale beslutningstagere for at prioritere effektivt mellem forskellige klimatilpasningstiltag og afbødningsstrategier når fremtidens byer skal klimasikres.

Byer er generelt karakteriseret ved stor heterogenitet, da mange forskellige overflade typer og areal-anvendelser typisk forekommer indenfor korte afstande. Dette udgør en stor udfordring for kortlægningen af bymiljøer i tilstrækkelig høj opløsning. Satellitbaserede metoder kan imidlertid med fordel anvendes i mange henseender, da disse ofte bidrager med en komplet rumlig og tidslig dækning om byområder, hvilket muliggør systematisk, præcis og ressourceeffektiv kortlægning af urban overflader og ændringer heri over tid. Satellit-baseret data om vegetationsdække kan anvendes til at kvantificere mængden og udbredelsen af befæstede arealer, eftersom de fleste større byer i Europa næsten udelukkende er kendetegnet ved en kombination af befæstede og grønne arealer. Resultatet af vores analyser for otte europæiske byer bekræfter dette og illustrerer at vegetations-data, som er målt ved analyse af Landsat satellitbilleder, kan anvendes til at estimere subpixel befæstelsesgrader med relativ stor nøjagtighed. Eftersom at vi kun observerer lav variabilitet i præcisionen imellem de forskellige byer, tyder det endvidere på, at metoden kan anvendes med tilsvarende nøjagtighed for byområder i andre regioner, både i og udenfor Europa. Vores resultater viser, at Soil Adjusted Vegetation Index (SAVI) er et overlegen indeks i forbindelse med udarbejdelsen af regionale regressionsmodeller til kortlægning for flere byer inden for et større geografisk område, og i de fleste tilfælde finder vi, at de lokale Landsat-baseret modeller let kan anvendes for byer i andre områder med kun et begrænset tab af præcision.

Vi har undersøgt konsekvenserne af nyere tids byudvikling og forventede fremtidige klimaændringer for oversvømmelser i forbindelse med skybrud for fire europæiske byer - Nice, Strasbourg, Wien og Odense. Byerne er udvalgt med udgangspunkt i at skulle repræsentere en væsentlig andel af mangfoldigheden af oversvømmelsesregimer, urbane morfologier, byudviklingsmønstre og hydrologiske respons, som findes på det Europæiske kontinent. Byudviklingsanalyserne viser, at de fire byer alle har oplevet en stigning i befæstelsesgraden i perioden 1984-2015, med absolutte stigninger fra 7-12 %. Samtidig finder vi at denne stigning primært skyldes, at byerne er vokset i omfang og i mindre grad på grund af en fortætning af det eksisterende bymiljø. Betydningen af byudvikling for urbane oversvømmelser viser en klar tendens i retning af en større effekt af ændringer i befæstede arealer for de mindst intense nedbørshændelser, og kun en marginal påvirkning af oversvømmelser fra skybrud med lange returperioder (de kraftigste hændelser). Herudover ses det, at ændringer i det urbane arealdække har stor betydning for udsathed overfor oversvømmelser for byer, som er karakteriseret ved grove jordteksturer og begrænsede forskelle i terræn, eftersom at infiltrationen, og samtidig effekten af at introducere befæstede arealer, her er høj. Byudvikling i perioden 1984-2015 forøgede det oversvømmede areal med 0-5 % hver gang befæstelsesgraden steg med 1 %, og påvirkede områder med de største vanddybder mest. Klimaændringernes indflydelse på fremtidige nedbørsintensiteter er analyseret for to klimascenarier, RCP (Representative Concentration Pathway) 4.5 og RCP 8.5, ved brug af ekstremværdi analyse og en "change-factor" metode. Der er stor

usikkerhed forbundet med de estimerede ændringer i nedbørsintensitet og hyppighed, men de gennemsnitlige klimafaktorer viser generelt en forøgelse i nedbørsintensiteten og sårbarheden overfor oversvømmelser i alle fire byer. Vores resultater viser en positiv sammenhæng mellem stigende returperioder og stigende koncentrationer af atmosfæriske drivhusgasser, og viser at de største ændringer kan forventes under de højeste klimascenarier, som f.eks. RCP 8.5. I Wien og Odense er konsekvenserne af byudvikling med henblik på byens sårbarhed overfor oversvømmelser sammenlignelige med hvad man kan forvente under RCP 4.5 scenariet, mens konsekvenserne i alle tilfælde er størst under RCP 8.5. I en klimatilpasningskontekst indikerer disse resultater en stor geografisk variation i effektiviteten af "grønne" klimatilpasningsløsninger, hvor naturlig infiltration og opbevaring af nedbør anvendes til at reducere oversvømmelser. Mens sådanne løsninger i nogle byer således vil være en effektiv strategi mod skybrudsrelaterede oversvømmelser, vil de kun være marginalt effektive i andre.

Konsekvensanalyser af klimascenarier og risiko-analyser for skybrud involverer en lang række kritiske antagelser og metodiske udfordringer som er relateret til usikkerheder i klimascenarier og modeller, konsekvensanalyser og økonomi. En metodisk ramme til integreret risikovurdering af klimaændringer er udviklet og anvendt på et casestudie af skybruds-relaterede oversvømmelser i Odense, Danmark. Metoden adresserer de komplekse sammenhænge mellem de forskellige typer af data, der er nødvendige i en klimatilpasnings kontekst, og understreger at tilgængeligheden af rumligt eksplicit data kan medvirke til at reducere den samlede usikkerhed og hjælpe med at identificere vigtige sårbare aktiver i forbindelse med beslutningstagning om klimatilpasning. Ved anvendelse af et integreret værktøj muliggøres kvantificeringen af den relative betydning af forskellige faktorer (valg af klimascenarie, værdisætning, diskonteringsfaktor m.m.), som påvirker det samlede resultat af risikovurderingen. En følsomhedsanalyse som undersøger 32 kombinationer af klimascenarier, skadeomkostningsmetoder og økonomiske variable, viser at alternative forudsætninger resulterer i risikoestimer med meget stor variation. En væsentlig kilde til usikkerhed kan relateres til klimafremskrivningerne og i særdeleshed til estimer af sandsynligheden for fremtidige ekstreme nedbørshændelser samt til de økonomiske forudsætninger, herunder risiko-aversion og diskonteringsfaktor. Når vi bevæger os fra vores nuværende klima til større atmosfæriske koncentrationer af drivhusgasser (GHG) indebærer det, at frekvensen af ekstreme hændelser stiger. I kombination med forskellige økonomiske antagelser finder vi, at de årlige skadesomkostninger for de højeste og laveste estimer varierer fra omkring 85 mio. EUR år⁻¹ ned til mindre end 1 mio. EUR år⁻¹. I en klimatilpasningskontekst er det dog vigtigt her at bemærke, at de fleste af kombinationerne vurderer risikoen til at være mellem 7 og 30 mio. EUR år⁻¹, mens kun 4 ud af de 32 kombinationer skiller sig ud og går langt ud over et risikoniveau på 30 mio. EUR yr⁻¹. Andelen af variationen i risikoestimerne, som kan tilskrives forudsætninger i klimafremskrivningerne er sammenlignelige med variationen, som skyldes forskellige antagelser omkring værdisætning og økonomi, og det kan derfor konkluderes at de økonomiske forudsætninger og klimascenarierne påvirker risikovurderingen på samme måde. Denne analyse viser at de faktiske forventninger til fremtidige klimascenarier og de økonomiske forudsætninger er meget vigtige i fastlæggelsen af risikoen fra ekstreme nedbørshændelser og dermed for niveauet for omkostningseffektiv klimatilpasning set fra et samfundsmæssigt perspektiv.

Udviklingslande er særligt sårbare over for klimaændringer på grund af lave indkomster, en svag infrastruktur og begrænset institutionel kapacitet. Ekstreme begivenheder gennem de seneste årtier indikerer en stigende hyppighed af hændelser og skader. Trods usikkerhed om, hvorvidt sådanne begivenheder bør tilskrives klimaforandringerne, er det vigtigt at styrke datatilgængelighed og metodeudvikling i forbindelse med at vurdere risici i sårbare udviklingslande. Vi foreslår at anvende specifikke forudsætninger til estimering af "willingness to pay" (WTP) for at undgå skader i de mindst udviklede lande, der afspejler risikoaversion og ulighed, ved at inkludere en ulighedsfaktor, som tilskriver relativ høj værdi for skader på fattige husholdninger. Resultaterne af vores analyser viser desangående, at anvendelsen af en ulighedsfaktor har stor indflydelse på WTP estimer for undgåede skader, og vi finder en faktor ti til forskel mellem de højeste og laveste årlige skadesomkostninger.

Dette tyder på, at sådanne forudsætninger er meget vigtige i relation til økonomiske argumenter for at investere i klimatilpasning i udviklingslande.

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Abbreviations

CF	Change Factor
FR	Fractional Vegetation Cover
GCM	General Circulation Model/Global Climate Model
IS	Impervious Surface(s)
LDC	Least Developed Country
MAE	Mean Absolute Error
MBE	Mean Bias Error
NDVI	Normalized Difference Vegetation Index
NPV	Net Present Value
OLI	Operational Land Imager (Landsat Satellite sensor)
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RP	Return Period
SAVI	Soil Adjusted Vegetation Index
TM	Thematic Mapper (Landsat Satellite sensor)
VI	Vegetation Index
WTP	Willingness to Pay

1 Introduction

1.1 Background

The economic and human consequences of extreme precipitation and related surface flooding in urban areas have been increasing rapidly in recent decades due to changes in a number of key factors affecting the overall exposure and vulnerability of the built environment. Globally, the total number of damaging hydro-meteorological events increased from ≈ 100 /year in the 1980s to 300/year in the early 21st century, causing overall losses to follow a similar trend (Munich RE, 2015). For Europe a comparable development, with increasing flood frequencies and economic losses, has been observed in the past thirty to forty years (Golnaraghi et al., 2014). Important drivers of these trends include climate change, expanding urban areas, general population growth and the accumulation of assets and people within cities. Continued urbanization and intensification (increased soil-sealing) of urban environments are projected for all regions (Angel et al., 2011; United Nations et al., 2014), which can be expected to make urban areas even more susceptible to flooding in the future. Recent forecasts of urban land cover for Europe project an average increase of 75% towards 2040, with values ranging from 6-289% (Angel et al., 2011). At the same time, urban populations in Europe are anticipated to rise by approximately 10%. For comparison in the least developed countries (LDCs), urban populations and urban land cover are both projected to more than double over the next thirty years, affecting vulnerability, risk and exposure to an even greater extent.

To address the challenge of increased susceptibility to urban flooding, all EU member states are required to conduct flood risk assessments during the period of 2007-2021, including the production of flood hazard and risk maps and the development of flood risk management plans, with a particularly focus on the impacts of climate change (European Commission, 2007). The directive applies to all kinds of floods (flash floods, urban floods, coastal floods, river flooding etc.) and aims to reduce the risk of adverse impacts to human health, economic activities, cultural and historical heritage and the environment. Cities are key players in the global and regional implementation of adaptation measures to climate extremes, as this is where the majority of people and economic activities are located, though there are large diversities in the ambition and preparedness of urban areas regarding the projected impacts of climate change. Adaptive capacity and GDP per capita are major drivers influencing the response to the challenges imposed to urban areas by climate change, and large cities in wealthier regions are often more involved in climate planning. In contrast, populations residing in cities in LDCs are often highly vulnerable and at greater risk of the impacts of present-day and future climate extremes. Increased knowledge of the main drivers of exposure to urban flooding regionally and locally is needed to support local and national authorities in reducing susceptibility towards pluvial flooding. Also, research and methodological development in a context of urban flood risk assessment and climate adaptation is necessary to provide decision-makers with the appropriate knowledge and tools to respond properly to the challenges posed by future climate change.

A key feature of cities is a high degree of imperviousness, as roads, buildings, parking lots and other paved areas occupy a main share of urban land areas. As a result, changes to impervious surfaces (IS) are often used as an indicator of urbanisation and urban development. The abundance and location of sealed surfaces is a key determinant of environmental quality, as it has important implications for many bio-physical processes, both regionally and locally (Arnold and Gibbons, 1996; Weng, 2012). For major urban areas, these processes are primarily linked to the hydrological cycle and the surface energy budget (e.g. Urban Heat Islands). Thus changes in the quantity and location of IS alter an area's hydrological response, since replacing natural land cover with artificial sealed surfaces reduces infiltration capacity, surface storage capacity and evapotranspiration (Parkinson and Mark, 2005; Butler, 2011; Hall et al., 2014). Moreover, it leads to increased run-off volumes, discharge rates, flood peaks and flood frequencies (Butler, 2004). For this reason, past and present city development patterns may prove to have (and will continue to have) important implications for the exposure of urban systems to pluvial flooding.

The detailed compositions of urban environments – as urban land-use is typically characterized by pronounced spatial and temporal dynamics – is a challenge in terms of mapping urban structure and development at the scale required for many applications, such as flood modelling, urban planning and risk assessments. Conversely, satellite imagery and remote-sensing techniques may provide complete temporal and spatial coverage of cities globally from the 1970s onwards, thus facilitating accurate, systematic and resource-efficient approaches for the mapping of urban landscapes at various scales. As urban development is observed at annual or even decadal timescales (urban development rates differ considerably between regions), temporal coverage is of great importance when selecting data for change analyses: while high-resolution satellite imagery only dates back to the late 1990s, medium-resolution data, including Landsat imagery, is available for the past thirty to forty years, allowing for extended time series of urban land cover. That said, most current satellite-based remote-sensing techniques for urban mapping are generally considered to be highly complex and resource-intensive (economic, data and software requirements are high), and are thus not yet readily available for many potential users, especially outside of the scientific community. In practice, this often restricts the use of such methods for a wide variety of applications, including urban flood modelling and analyses of the importance of urban development and structure in the contexts of climate change and extreme events.

Climate change is often described as a long-term phenomenon characterized by changes in global mean parameters such as temperature or precipitation, one which plays an important role in developing climate policies and long-term mitigation and adaption strategies. When it comes to risk assessments, on the other hand, information relating to the tails of the probability distributions (i.e. extreme events with low probabilities) is typically of much greater interest, as many adverse effects of climate change are propagated through changes in the intensity and frequency of climate extremes. Future climate change is expected to increase the intensity and frequency of precipitation extremes in both the short and long terms for most regions, including Europe, and the projected changes often show a positive correlation with increasing concentrations of atmospheric greenhouse gasses (Fowler and Hennessy, 1995; Larsen et al., 2009). As a result, the most severe changes are projected under high-end scenarios like the Representative Concentration Pathway (RCP) 8.5 (Meinshausen et al., 2011; Field et al., 2012). This can lead to further increases in the exposure of urban areas to flooding unless suitable adaptation measures are implemented. Projections of high-intensity precipitation both locally and regionally are associated with large uncertainties due to different sources of error, including an incomplete understanding of precipitation processes in climate models. Hence ensemble approaches, where precipitation changes are analysed for a large number of climate models and scenarios, are often preferred in order to improve quantifying the influence of uncertainties on projections of future climate extremes. Using information from combinations of General Circulation Models (GCMs) and Regional Climate Models (RCMs) enables the investigation of variations in precipitation projections for flood risk assessments and facilitates robust adaptation decision-making.

Risk assessments of urban flooding require an integrated approach in which detailed information on extreme precipitation characteristics (e.g. from extreme value analysis of climate model projections), land cover, land use, human behaviour and economics are combined to provide decision-makers and other stakeholders with specific knowledge of the risks of the diverse array of assets that exist within urban environments. Integrated risk assessments are surrounded by large uncertainties originating from the different types of analysis involved and the complex linkages of different analytical tools, including climate models, physical impact models (e.g. flood models) and socioeconomic damage assessments. Altogether this plethora of uncertainties provides the basis for a wide range of climate change risk estimates. Assuming that the level of risk defines the upper boundary of what society should be willing to spend on adaptation measures, this likewise implies a wide range of appropriate responses to climate change. Least developed countries (LDCs) are particularly vulnerable to climate change and to the adverse impacts of extremes due to their low incomes, weak infrastructure and limited institutional capacity for coping with climate change. Also limited data availability often hinders the application of detailed geographical information to climate projections, land cover and socioeconomics, including accurate damage costs. Extreme events which have occurred in recent decades point to the threat of an increasing frequency of incidents and damage. Despite uncertainties

over attributing these events to climate change, it is important to strengthen the data and methodological frameworks used for assessing risks in LDCs further.

1.2 Research objectives

This thesis **(1)** aims to improve our current understanding of the importance of urban development and climate change for the exposure of urban areas to pluvial flooding. Systematically quantifying the importance of changes to urban land cover and climate change in relation to flooding events will assist local and national decision-makers to prioritize effectively between different adaptation measures - and in some cases also mitigation strategies - when planning the climate-proofing of cities in the future. As a precondition for addressing this objective, a satellite-based remote-sensing methodology for quantifying historical urban development, which is particularly useful in an urban flood modelling context, will be developed and tested, i.e. to enable a resource-efficient mapping of temporal and spatial changes in impervious surfaces, which may be useful also for a wide array of other applications for cities globally. Secondly, through the development and application of an integrated risk-assessment framework, this thesis **(2)** aims to advance the current knowledge of the importance of key uncertainties and assumptions in climate projections, impact analysis and economic valuation in risk assessments of climate extremes in the context of climate change adaptation. Assuming that the estimated level of risk also determines the level of appropriate adaptation, a disaggregated approach, in which the importance of individual assumptions is highlighted, facilitates knowledge for robust decision-making when adapting to climate change.

Publication I investigates the accuracy of using vegetation indices to estimate impervious surface fractions for European cities at a resolution that is suitable for urban development analysis and large-scale urban flood modelling. **Publication II** uses the findings of publication I to examine the potential for developing a combined remote-sensing and flood-modelling approach to quantify the impacts of recent urban development and expected future climate change on pluvial flood exposure. The developed method is evaluated through a case study of the city of Odense, Denmark. **Publication III** refines the method developed in publication II i.e. by improving the applied flood model and the urban development analysis, as well as through the introduction of uncertainty estimates for the impacts of urban development and climate change on pluvial flooding. It also aims at improving current understanding of the relative impacts of soil-sealing and climate change on exposure to flooding by adding three additional case studies of cities, which are largely representative for European cities. **Publication IV** addresses the importance of uncertainty in climate projections, impact assessments and economic valuation for risk assessments in a climate adaptation context through a case study of urban flooding; the case study is carried out in Odense, and this thematically links to publication II. **Publication V** considers an integrated risk assessment framework for addressing the complex linkages between the different kinds of data and analytical tools generally required to carry out risk assessments supporting climate adaptation decision-making in urban areas. Finally, **Publication VI** presents and applies an adjusted risk-assessment framework suitable for adaptation analyses in least developed countries that are particularly vulnerable to the impacts of climate extremes, that is, due to their low incomes, weak infrastructure and public institutions and thus a low capacity for coping with the adverse impacts of climate change.

Research objective **(1)** is addressed in publications **I, II** and **III**.

Research objective **(2)** is addressed in publications **IV, V** and **VI**.

1.3 Methodological framework

Urban development and climate change are both expected to affect the exposure of urban areas to pluvial flooding. Increased soil-sealing as a result of urban development influences the hydrological response, causing elevated run-off volumes, while climate change is projected to increase the intensity and frequency of climate extremes.

A combined flood-modelling and remote-sensing approach has been developed to simulate the occurrence of (and related flooding during) a range of design extreme precipitation events for four cities (Nice, Strasbourg, Vienna and Odense) in Europe under current and expected future climatic conditions. To include the influence of temporal variations in urban land cover (changes in imperviousness), the simulations are performed for different levels of urbanisation, which corresponds to the historical (1984) and current (2013-2015) conditions of these cities. Nice, Strasbourg, Vienna and Odense are selected for analysis to represent different climatic conditions, (expected) dissimilar historical urbanisation trends, and varying soil characteristics and topographies (flat vs hilly), which are important for infiltration processes during extreme precipitation. The impacts of future climate change for exposure to urban flooding are examined for two different climate scenarios, i.e. RCP 4.5 and RCP 8.5 (van der Linden and Mitchell, 2009). The RCP 4.5 scenario describes a future with increases in the near-surface air temperature towards 2100 of 1.8°C (1.1-2.6°C), while the RCP 8.5 scenario represents a world where the increased radiative forcing corresponds to an increase of 3.7°C (2.6-4.8°C) in 2100 (Intergovernmental Panel on Climate Change, 2014).

Data-processing and analytical procedures are divided into three separate types of analysis: (a) urban development analysis; (b) flood modelling; and (c) quantification of the influence of urban development and climate change on exposure to flooding (Figure 1-1). Initially, Landsat TM (1984) and Landsat OLI (2013-2015) satellite imagery is analysed to quantify IS fractions at a pixel level for historical and current urban land cover conditions. The outputs of the remote-sensing analyses are combined with soil infiltration data and regionally downscaled estimates of current and expected future precipitation extremes to enable 2D overland flow simulations and flood hazard assessments within a flood modelling framework. Flood hazard maps, indicating the extent and depth of flooding, are calculated for various combinations of urban land cover, extreme precipitation severity (return period) and climate scenario (an example of a flood hazard map is shown in Figure 3-1). A cross-comparison of multiple flood-hazard maps allows for quantification of the relative importance of changes to urban land cover as compared to climate change for overall exposure to pluvial flooding. The impact of recent urban development is isolated by simulating the occurrence of identical design precipitation events for both historical and current levels of urban IS fractions. Conversely, design precipitation intensities are varied, and imperviousness kept constant, when evaluating the expected impacts of climate change. A total of 48 combinations of input variables with regard to degree of imperviousness, climate scenario, climate factors, return period and soil water infiltration are simulated for each city (Figure 3-2). The impacts of future urban development are not included directly in this study, as such projections are surrounded by substantial uncertainties and are not considered by the authors to contribute additional clarification of the role of urban development for temporal variations in exposure to flooding.

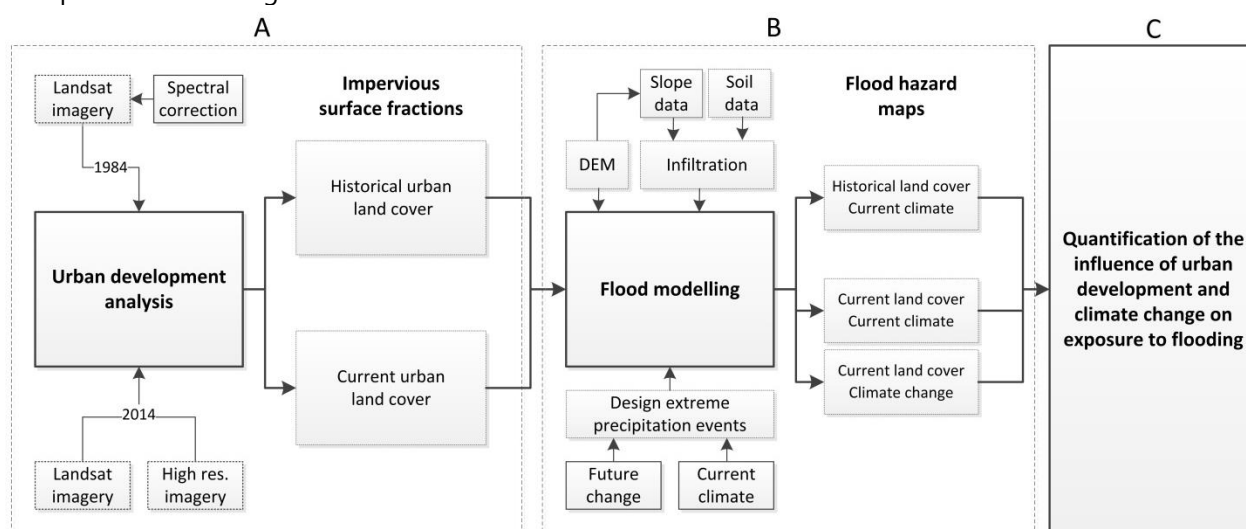


Figure 1-1. Methodological framework for quantifying the impacts of changes to urban land cover and climate change for the exposure of cities to pluvial flooding (Paper III, Fig.1).

1.4 Thesis structure

This PhD thesis comprises three parts. The first part consists of a summary describing the key content and findings of the six scientific publications that are included in the thesis. This is followed by a discussion of the implications of these findings and perspectives for the directions of future research within this scientific area. The table below shows the relationship between the sections in the summary and the six scientific publications (chapters), which comprise the third part of the thesis. In those cases where the summary contains new material that is not included in the scientific publications, this has been carefully highlighted.

	Sections	Publications
1	SUMMARY OF PUBLICATIONS	
	2. Urban development analysis	I-III
	2.1 Remote-sensing of impervious surfaces	I
	2.2 Accuracy assessment	I
	2.3 Change analysis for 1984-2014	II-III
	3. Flood modelling	II-III
	3.1 Flood-hazard mapping	II-III
	3.2 Impact of soil-sealing on urban hydrology during extreme precipitation	III
	3.3 Climate change impacts on extreme precipitation	II-III
	4. Risk assessment of climate extremes	IV-VI
	4.1 Framework for integrated risk assessment	IV-VI
	4.2 Damage cost assessment	V
	4.3 Uncertainties in climate scenarios, impact analysis and economics	IV-VI
	5. Results	III-VI
	5.1 Impacts of urban development and climate change on pluvial flooding	III
	5.2 Risk assessments	IV-VI
	5.2.1 Flood risk assessment for the city of Odense	V
	5.2.2 Sensitivity analysis	IV
	5.2.3 Least developed countries: a case study from Cambodia	VI
2	IMPLICATIONS, CONCLUSIONS AND PERSPECTIVES	
	6. Discussion	I-VI
	6.1 Impacts of urban development and climate change on pluvial flooding	II-III
	6.2 Remote sensing of impervious surfaces	I
	6.3 Risk assessments of pluvial flooding	IV-V
	6.4 Risk assessments of climate extremes for least developed countries	VI
	7. Conclusions and perspectives for future research	I-VI
3	PUBLICATIONS	I-VI

Table 1-1. Relationship between the sections in this thesis and the publications included in it.

2 Urban development analysis

2.1 Remote sensing of impervious surfaces

Vegetation indices (VIs), like the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1974; Tucker, 1979) and the Soil Adjusted Vegetation Index (SAVI) (Huete, 1988), have a long record of success within the remote-sensing community, and several authors have shown them to provide relatively accurate estimates of the quantity and distribution of IS and urban land cover (Carlson and Traci Arthur, 2000; Bauer et al., 2002; Bauer et al., 2008; Yuan et al., 2008). The use of VIs as a method to estimate urban IS fractions is based on the assumption of a strong inverse relationship between vegetation cover and IS within cities (Figure 2-1)– that is, it is implicitly assumed that non-IS within urban areas are covered with green vegetation. Lakes, rivers and other major waterways are common in many urban areas, but these are easily identified and masked out due to the spectral signature of water, which is highly distinguishable from other urban surfaces. Limitations in using VIs for IS mapping include the influence of bare soils, shadow effects from buildings and tree crowns covering IS (Bauer et al., 2008). Arguably, bare soil, the most critical of the three, has similar spectral characteristics to urban fabrics and hence is often confused with IS (Lu and Weng, 2006; Weng, 2012). In a flood modelling context, the confusion of bare soils with IS is particularly important, as the hydrological response during extreme precipitation differs considerably between the two surface types.

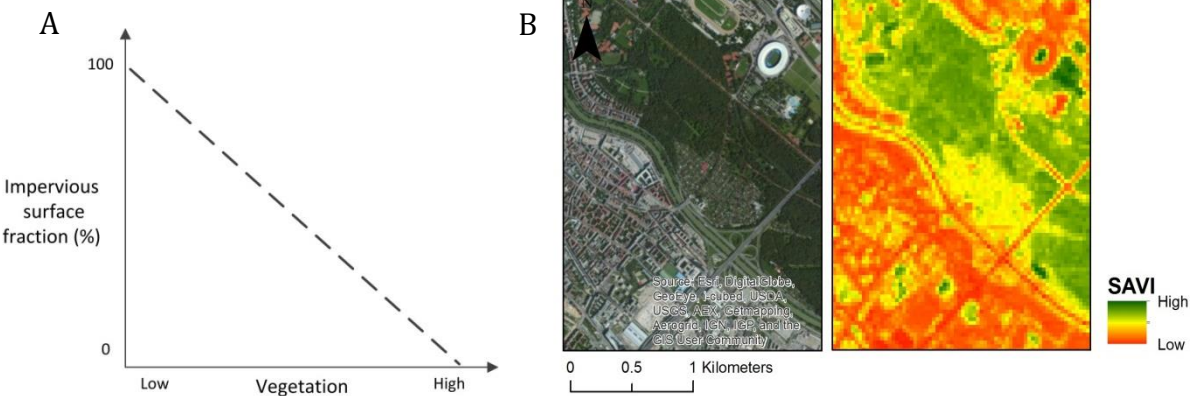


Figure 2-1. (A) Conceptual relationship between impervious surface fractions and vegetation cover/vegetation indices in urban environments (adapted from Bauer et al., 2008). (B) Example of a high-resolution image used to measure reference impervious surface fractions and a Soil Adjusted Vegetation Index (SAVI) calculated from Landsat OLI for a central part of Vienna (publication III, Fig. 2).

To test the accuracy of applying estimates of vegetation cover to mapping IS and temporal changes in it for different geographical settings, medium resolution (30m) Landsat 8 satellite imagery is used to calculate three different vegetation indices (Normalized Difference Vegetation Index or NDVI, Soil Adjusted Vegetation Index or SAVI, and fractional vegetation cover or FR) for eight cities in Europe, representing different vegetative and climatic conditions (Figure 2-2). Detailed information on the three indices can be found in publication I, section 2.2.

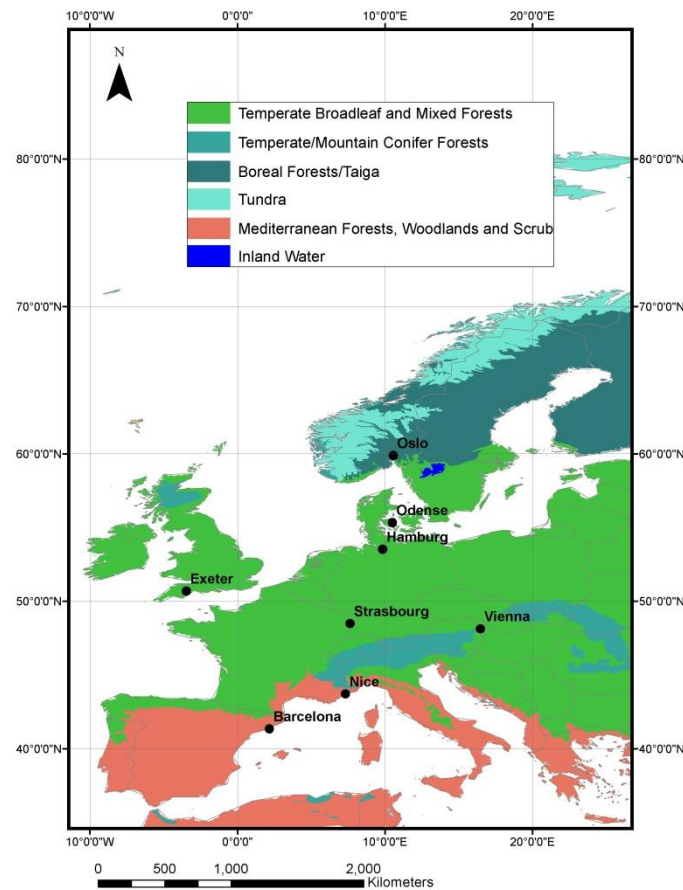


Figure 2-2. Location of case cities used in the evaluation of the Landsat-based estimates of impervious surface fractions. For comparison, the major terrestrial ecoregions in Europe are shown (The Nature Conservancy, 2015) (publication I, Fig. 1).

High-resolution aerial imagery is manually digitized to create reference IS data for minor subsets of each of the cities and is applied to develop city-specific regression models between vegetation cover of IS fractions and to validate the accuracy of the Landsat-based estimates. Also, regional regression models are developed by compiling data from multiple cities to examine the potential for developing and applying a single regression model to estimate IS fractions for numerous urban areas. To evaluate the spatial transferability of the regression models, we estimate the loss of accuracy when using a transferred model (e.g., a model developed for another city) as compared to a local model. The performance of the regression models is evaluated by calculating the Mean Absolute Errors (MAE) and the Mean Bias Errors (MBE) of the VI-based IS estimates as compared to the reference IS fractions (publication I, Equations 5 and 6). The MAE is defined as the absolute difference between the observed (reference data) and the predicted (satellite estimates) IS fractions at a grid cell level. Conversely, the MBE is a measure of the average model "bias", i.e. how much the model under- or overestimates imperviousness for the entire area. Major areas characterized by bare soil (e.g. agricultural areas) are excluded by establishing city boundaries by conducting manual digitalization of the Landsat scenes prior to developing and training the regression models. Likewise, the final regression models are only accurate for urban areas where the proportion of bare soils is negligible. Also, as mentioned previously, major waterways are masked out during initial pre-processing of the satellite imagery.

2.2 Accuracy assessment

All three indices are found to provide fairly accurate estimates of subpixel imperviousness with average MAEs and absolute MBEs of 10-12% and 0-3% respectively for the local models, (Figure 2-3), increasing only moderately for the regional and spatially transferred models (Figure 6-1a, discussion). The Landsat estimates are found to be most accurate for areas covered with high levels of imperviousness (90%–100%) with average MAEs of approximately 5%, while increasing to 10%–16% for

lower levels of imperviousness (Figure 2-3a). The better performance for areas with very high IS fractions is partly a consequence of the location and characteristics of the urban sub-areas (from which the regression models were developed), which are located within the central parts of the cities and are therefore characterized by a high degree of imperviousness. A bias towards an overestimation of low values and an underestimation of high values is observed for all the cities and indices (Figure 2-3b). This pattern is most likely caused by the inability of the models to adequately describe the non-linear relationship between NDVI/SAVI and IS fractions. The VI/IS relationship is found to be similar for cities that are characterized by comparative vegetative and climatic conditions, and cross-validation of the developed models shows equivalent results, with relatively low MAEs and MBEs for a number of different combinations of city-specific models and urban sub-areas. A low variability in accuracies between the different cities indicates that information on vegetation cover from Landsat may be equally accurate in estimating urban land cover for many other urban areas globally (Figure 6-1b, discussion). Also, our findings suggest that the regional models can be applied more broadly to multiple urban areas and that accuracy is reduced only marginally by applying the regional models (Figure 6-1a, discussion). SAVI is identified as a superior index for the development of regional quantification models and in a spatial transferability context (Figure 6-1a, discussion). As compared to NDVI, SAVI reduces the influence of variations in soil background colour and building materials and consequently improves the inter-city comparability of the regression models, which arguably could be the reason for the better performance of the models based on SAVI.

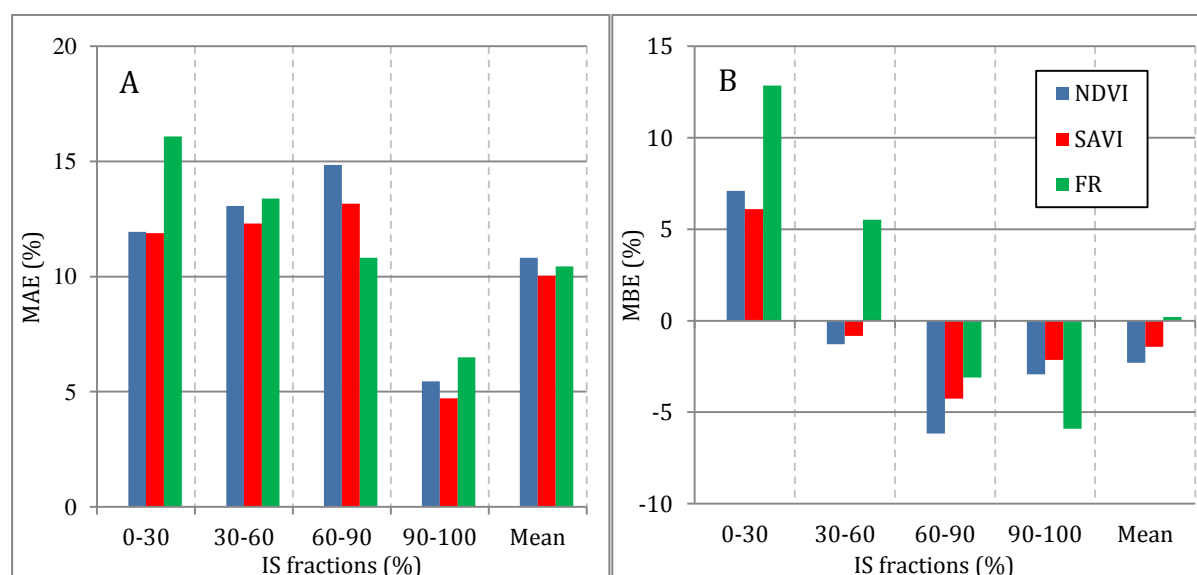


Figure 2-3. (A) Average MAEs and (B) MBEs for different levels of imperviousness for all the urban sub-areas for the local linear regression models of NDVI/SAVI and for FR (publication I, Fig. 7, adjusted versions).

2.3 Change analysis for 1984-2014

Urban areas are commonly dominated by man-made IS, changes in which are often used as an indicator of urban development (Weng, 2012). As major European urban areas are almost exclusively characterized by a combination of IS and green vegetation (and in some cases water, which is easily distinguishable and masked out), information on vegetation cover from remote sensors can be utilized to provide accurate and cost-efficient estimates of the quantity and spatial distribution of IS and changes to it.

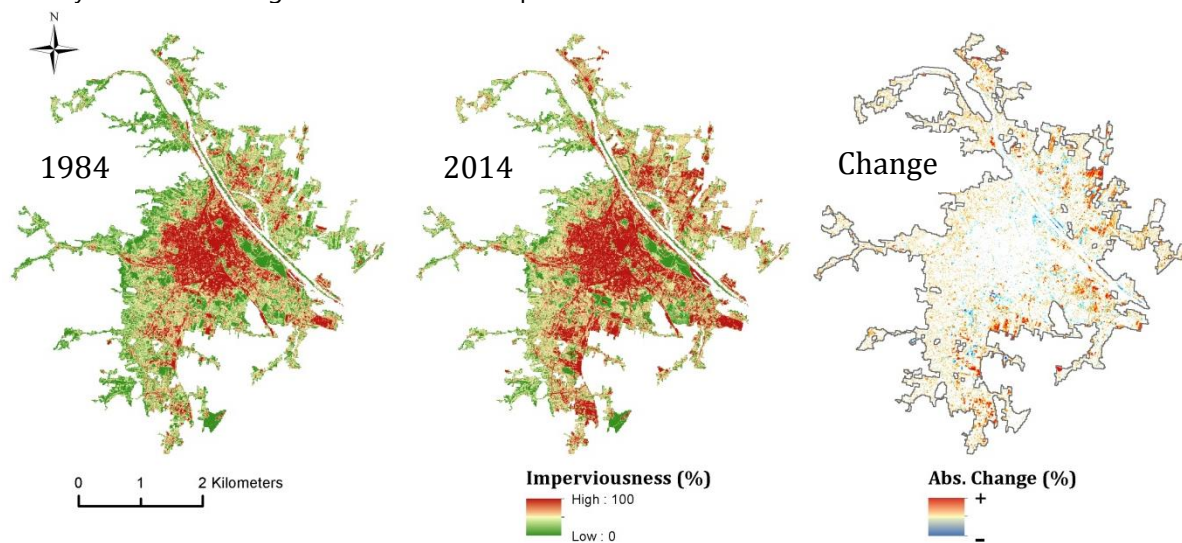
As already noted, the urban development analysis focuses on four cities (Nice, Strasbourg, Vienna and Odense) representing different climatic conditions, varying soil infiltration properties and an (expected) range of urban development trends. Linear regression models developed by Kaspersen et al., 2015 (publication I) relating SAVI and imperviousness are applied to estimate IS fractions for the historical

and present-day versions of the four cities. Impervious surface fractions for individual grid cells are calculated using equation 1.

$$\text{Impervious surface fraction} = a * SAVI + b \quad (1)$$

Multiple Landsat images are compiled into Maximum Value Composites (MVCs) of SAVI to reduce the influence of inter-annual and intra-annual variations in the timing of maximum vegetation cover. Initial IS fractions are subsequently corrected for pixel values <0% and >100%, as linear regression models do not constrain the data within the range that is physically possible (0-100%). Impervious surface fractions are estimated at a spatial resolution of 30 m, which is the original resolution of the short wave (visual and near-infrared) bands in the Landsat TM and OLI sensors. The spatial resolution is later resampled to 25 m to match the resolution of the Digital Elevation Model (DEM), which is used for overland flow calculations in the flood model. In order for the reflectance data, and therefore the SAVI images and IS fractions, to be comparable between the Landsat TM (historical images) and OLI sensor, the difference in the spectral response function between the two sensors is corrected for by applying conversion factors to the surface reflection in individual bands (Flood, 2014). Detailed information on the pre-processing of the Landsat data is found in publication I, section 2.5.

The results of the urban development analyses show that the four cities have all been experiencing increased levels of imperviousness during the past thirty years, with absolute changes ranging from 6.6% in Nice to 11.6% in Strasbourg (Figure 2-4). From visual inspection, we find that the increase in sealed surfaces is driven primarily by cities expanding into former non-urban areas. However, there is also a tendency for existing urban land cover to intensify in all four cities. Detailed quantitative analyses of the location of change are highly relevant for other applications, including in risk assessments, but this is outside the scope of the paper, as we are here only examining the influence of the key drivers of changes to urban flood exposure in cities.



	France	Austria	Denmark	France
	Strasbourg	Vienna	Odense	Nice
1984	41.4%	42.2%	29.1%	38.1%
2014	53.0%	53.5%	36.6%	44.7%
Change	11.6%	11.3%	7.5%	6.6%

Figure 2-4. Urban development analysis for Vienna during 1984-2014 and impervious surface fractions and changes to them for Strasbourg, Vienna, Odense and Nice during 1984-2014 (2013-2015) (publication III, Table 2; images from Vienna are not included in any of the publications).

3 Flood modelling

3.1 Flood-hazard mapping

Overland flooding can occur during extreme precipitation when the sewer system is surcharged or when soil infiltration and storage capacities are exceeded, and excess surface water can pond on the surface or flow in preferential flow paths along streets or between buildings, depending on the local topography. When simulating overland flooding several modelling concepts are available, including 1D simulations using information on local depressions or simple hydrodynamic drainage system models and more advanced 2D and 1D/2D representations of surface and subsurface flows during precipitation. The pros and cons of these methods have been widely discussed, and the choice of method is highly dependent on the aim of the study: for example, 1D solutions are fast but offer a poor approximation of complex (non-unidirectional) flows (Mark et al., 2004; Leandro et al., 2009; Obermayer et al., 2010). The current study uses the 2D overland flow model in MIKE 21 (MIKE by DHI, 2014) to compute water-level variations, surface flows and maximum flood depths in response to the occurrence of a variety of precipitation extremes.

Reported Intensity – Duration – Frequency (IDF) curves, which are derived based on historical precipitation measurements from weather stations located in (or in the surrounding area of) each of the four cities, are applied to construct time series of design precipitation events for 5, 10, 20, 50 and 100-year return periods (Coste and Loudet, 1987; Gregersen et al., 2014; BMLFUW, 2016). These time series are considered representative of precipitation characteristics in both 1984 and 2014. Climate change factors are quantified from climate model simulations and applied to the present-day IDF curves to provide information on future precipitation extremes under the RCP 4.5 and RCP 8.5 climate scenarios (see section 3.3 and publication III for details on extreme value analysis). The EU DEM, which offers elevation estimates over the European continent at a 25m spatial resolution, is used as the basis for calculating surface water flows after onset of precipitation (EEA, 2016). Soil-water infiltration rates are calculated for each grid cell by combining IS fractions with information on soil textures and average slope at the city level (see section 3.2 for details). As the flood modelling approach used here (MIKE 21) does not include a representation of the urban drainage system, the drainage capacity of the pipes is modelled by modifying the precipitation input, for example, by assuming a general maximum pipe capacity based on precipitation intensities. In the current analyses, maximum drainage capacities are assumed to correspond to precipitation with a return period of five years under present-day climatic conditions, and the intensity of all other precipitation events is reduced to reflect this assumption (Chow et al., 1988). This implies that surface flooding does not occur in any of the cities for precipitation with return periods of five years or less. The primary outputs of the flood modelling are flood hazard maps showing the maximum flood depth and extent for each individual simulation (Figure 3-1).

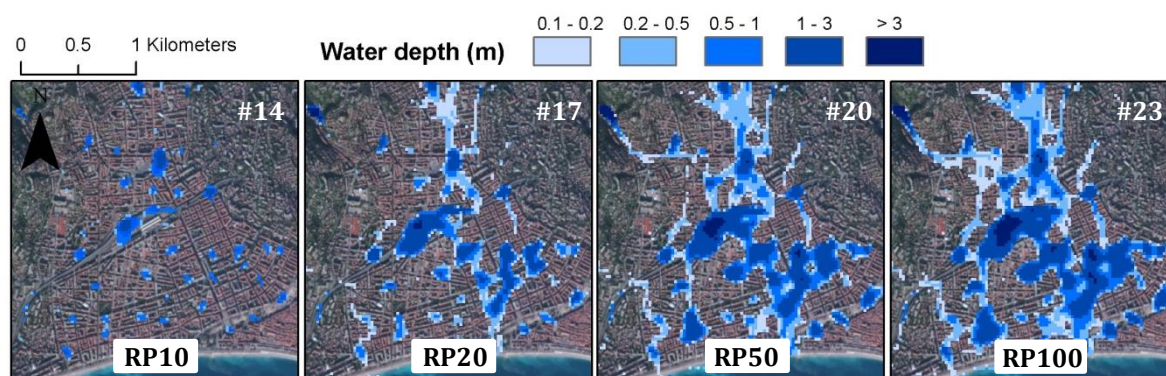


Figure 3-1. Flood hazard maps for Nice showing the maximum water depth and extent during extreme precipitation with a return period of 10-100 years for current urban land cover, present-day climate and average soil infiltration. # = simulation number in Figure 3-2 (publication III, Fig. 3).

For each of the four cities, a total of 48 flood-model simulations are conducted to represent variability in urban land cover, climate scenario, precipitation return period, climate factors and soil-water infiltration (Figure 3-2). Twelve of these are performed for historical levels of imperviousness, while an additional 36 are conducted for current (2014) versions of the cities (RCP 4.5 and RCP 8.5 are run with urban land cover as in 2014). High and low climate change factors and soil infiltration rates are included to examine the importance of uncertainties in influencing the calculated impacts of urban development and climate change for overall flood exposure and changes to it.

Urban Land cover	Climate scenario	Precipitation event	Climate factor	Soil infiltration	#
1984	Present day	RP10	No change factor	Low	1
				Average	2
				High	3
		RP20		Low	4
				Average	5
				High	6
		RP50		Low	7
				Average	8
				High	9
		RP100		Low	10
				Average	11
				High	12
2014	RCP 4.5	RP10		Low	13
				Average	14
				High	15
		RP20		Low	16
				Average	17
				High	18
		RP50		Low	19
				Average	20
				High	21
		RP100		Low	22
				Average	23
				High	24
	RCP 8.5	RP10	10 th percentile	Average	25
			Average		26
			90 th percentile		27
		RP20	10 th percentile		28
			Average		29
			90 th percentile		30
		RP50	10 th percentile		31
			Average		32
			90 th percentile		33
		RP100	10 th percentile		34
			Average		35
			90 th percentile		36
RCP 4.5	RP10	10 th percentile	37		
		Average	38		
		90 th percentile	39		
	RP20	10 th percentile	40		
		Average	41		
		90 th percentile	42		
	RP50	10 th percentile	43		
		Average	44		
		90 th percentile	45		
	RP100	10 th percentile	46		
		Average	47		
		90 th percentile	48		

Figure 3-2. Overview of flood model simulations performed for each city. RP = return period, RCP = Representative Concentration Pathway (this figure is not included in any of the publications).

3.2 Impact of soil-sealing on urban hydrology during extreme precipitation

Converting pervious surfaces to impervious surfaces, or soil-sealing, is one of the most pronounced consequences of recent urban development and is an important determinant of the hydrological response of cities during extreme precipitation. As run-off is the proportion of precipitation which does not infiltrate, soil-infiltration properties, which are primarily controlled by soil texture, topography (slope) and soil structure (granular vs compact soils), are important (together with degree of soil-sealing) in determining run-off volumes. We hypothesize that the impact of urban development is most pronounced for cities characterized by coarse soil textures and limited topography, as soil-infiltration rates are excessive here, and because soil-sealing has a greater impact on the urban hydrological response during extreme precipitation in such areas. Similarly, the influence of changes to urban land cover is expected to be more prominent for the most frequent precipitation events (i.e. RP10), while only affecting the hydrological response for the most extreme events (i.e. RP100) to a lesser degree. The background to this is an inverse relationship between the soil saturation time and the intensity of precipitation, causing run-off from pervious surfaces to increase with the intensity of

the events. For purposes of the current research run-off, is calculated at a grid-cell level for each time-step in the precipitation time-series using the following equation (2):

$$\text{run-off} = \text{precipitation rate} - (\text{infiltration rate for pervious surfaces} * (1 - \text{imperviousness})) \quad (2)$$

Soil-infiltration rates are estimated for each city using information on the dominant soil texture and average slope over the entire urban area (see publication III, section 2.4 for details). A constant infiltration rate is applied during the entire time of precipitation for all design events, and an initial loss (causing a decreasing infiltration rate with time) is not included, as its importance has been found to be negligible for total infiltration/run-off during extreme precipitation (J. J. Stone et al., 2008). Also, as a consequence of the large degree of uncertainty in local infiltration rates, which would only be increased further by including a more complex description of the infiltration rate over time, a constant rate was preferred in the current study. Despite the fact that soil texture and structure vary considerably over short distances, a single infiltration value was applied for all grid cells within the individual cities. This simplification is required to enable the application of the same soil texture data across the different cities. High and low values of potential infiltration are included to examine the sensitivity of the results of the analysis to variations in this parameter and to provide a quantitative measure of uncertainty in analyses of the impacts of urban development (i.e. soil-sealing) on pluvial flood exposure. On the basis of the variations in the estimated soil-infiltration rates, the effect of changes in IS (i.e. urban development) on exposure to flooding is expected to be greatest for Odense and smallest for Nice, as the impact of soil-sealing affects run-off volumes more for areas characterized by high infiltration rates (Table 3-1).

(mm/hr)	France	Austria	Denmark	France
	Strasbourg	Vienna	Odense	Nice
High	30.6	46.2	58.6	20
Average	15.3	23.1	29.3	10
Low	7.65	11.55	14.65	5

Table 3-1. Potential soil infiltration rates (mm/hr) for pervious areas in the four cities, calculated based on primary soil texture and average slope within the cities. Low = 0.5 * average, high = 2 * average, adapted from USDA, 2016 (publication III, Fig. 4).

The relationship between precipitation rate, potential infiltration rate and run-off is exemplified using information from Vienna (Figure 3-3a). Here it is seen that run-off from pervious surfaces does not start until midway through the precipitation event, and only continues for 20-25 minutes before the precipitation rate again drops below what can be infiltrated into the soils. However, as most of the precipitation falls within this short period of time, total run-off approximates to 30%. Run-off from pervious surfaces is naturally higher for the most extreme events and decreases for precipitation with shorter return periods (Figure 3-3b). As a consequence of geographical differences in precipitation characteristics, degree of imperviousness and soil-infiltration properties, run-off from pervious surfaces varies significantly between the different cities, ranging between 22-34% for Odense, while increasing to 72-88% for Nice. A similar trend is present when examining the actual run-off from the different urban areas (Figure 3-3c), although values are elevated here as a result of the inclusion of the estimated urban IS fractions for 1984 and 2014. A minor increase in run-off during 1984-2014 can be identified for all the cities, as average imperviousness is also found to increase during this period (Figure 2-4).

The large variation in run-off between the examined cities indicates that the effectiveness of simply reducing overall imperviousness at the city level as a measure to protect urban environments from pluvial flooding is highly dependent upon the relationship between local infiltration rates and the intensity of extreme precipitation. Also, local infiltration capacities are found to reduce flood levels the least for the most extreme events (e.g. RP100), suggesting that alternative adaptation measures should be preferred when protecting against flooding during very extreme precipitation. This implies a diverse

array of solutions when planning for pluvial flood-proof cities at different geographical locations and when adapting to the impacts of precipitation with alternative return periods.

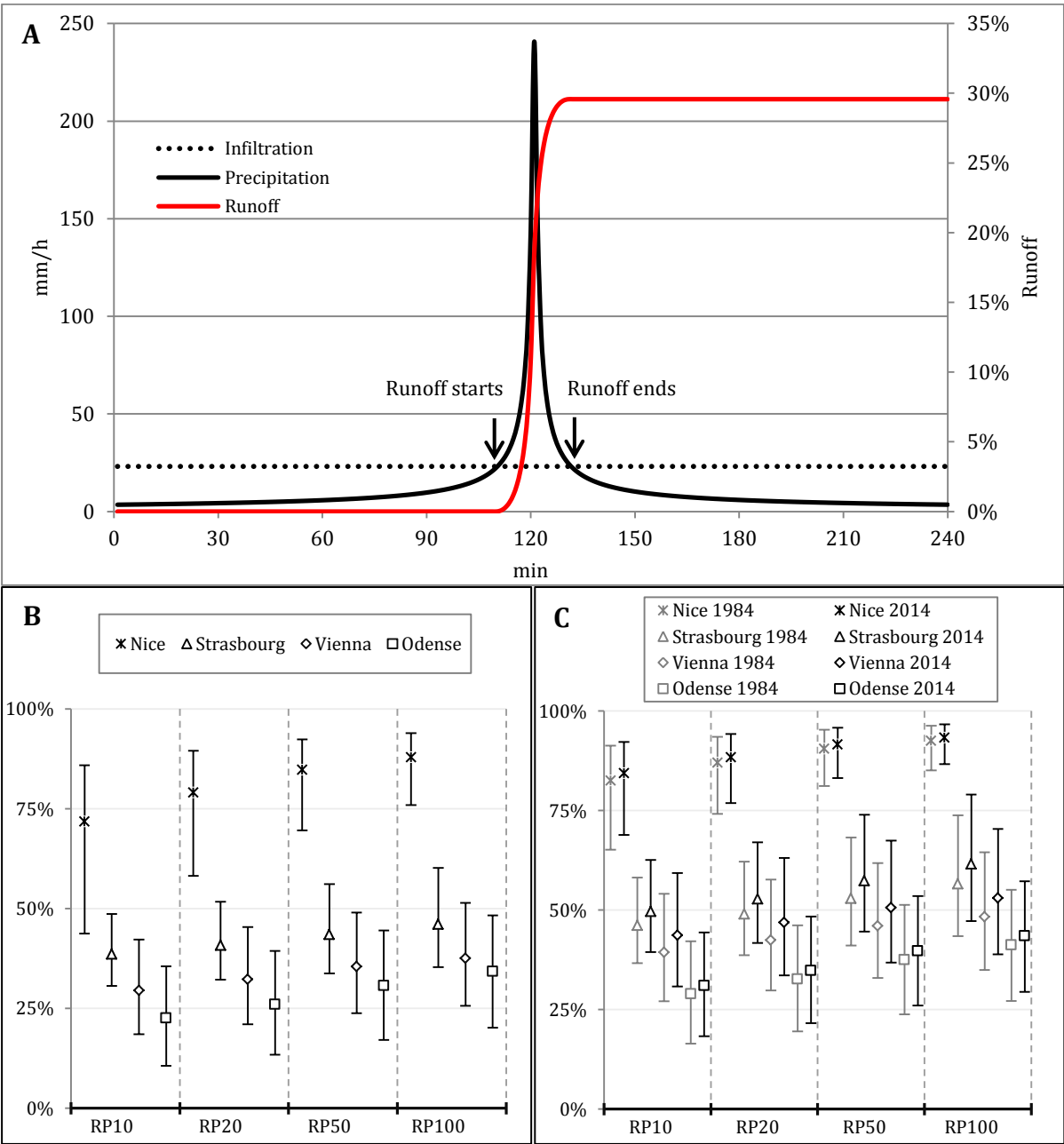


Figure 3-3. (A) Precipitation rate (RP10), potential infiltration rate (average) and cumulated run-off (RP10) from pervious surfaces for Vienna. (B) Run-off from pervious surfaces during extreme precipitation with different return periods (RP10–RP100) under present-day climatic conditions. (C) Runoff from urban areas during extreme precipitation with different return periods (RP10–RP100). Error bars represent low/high infiltration rates; 1984 = imperviousness in 1984; 2014 = imperviousness in 2014 (publication III, Fig. 5).

3.3 Climate change impacts on extreme precipitation

High-resolution (i.e. at a city-level) climate projections for precipitation extremes can be estimated from global coupled atmosphere-ocean circulation models (GCMs) and downscaled using regional climate models (RCMs) and/or empirical-statistical approaches (Willems, 2012). To address the considerable uncertainties associated with analyses of the frequency and intensity of future extreme precipitation, such projections are generally based on multi-model ensembles, rather than single-

model projections (van der Linden and Mitchell, 2009; Gregersen et al., 2013; Sunyer et al., 2014; Sunyer et al., 2015).

The impact of climate change on extreme precipitation is estimated using a change factor (CF) methodology, that is, by comparing the relative change between climate model outputs for present-day and future precipitation (Willems, 2012; Sunyer et al., 2014). Extreme value analysis is conducted for present-day (1986-2005) and future (2081-2100) time slices for maximum hourly precipitation (within one day) to calculate intensities for 5, 10, 20, 50 and 100-year return periods (RPs). Change factors, representing the percentage difference between present-day and future precipitation intensities, are estimated under the RCP 4.5 and RCP 8.5 climate scenarios for the ten Cordex simulations of SMHI, which use the RCA4 RCM and different GCMs to highlight variability in model responses to future changes in radiative forcing (Giorgi et al., 2009). Three different change factors are estimated for each city for each climate scenario (RCP 4.5 and RCP 8.5), representing the 10th and 90th percentiles and averages for the ten model combinations (change factors can be found in publication III, table 2). Multiple change factors are selected to represent (some of) the uncertainty (80% of the models are within the 10th and 90th percentiles) in climate model projections of future extreme precipitation. The results of the extreme value analysis show a general increase in extreme precipitation intensity for all locations and return periods and for both RCP 4.5 and RCP 8.5. Also, average change factors are found to increase more for the most extreme events (highest change factors for RP100) and in most cases follow that of global climate change (higher factors for RCP 8.5 as compared to RCP 4.5). We observe a large variation in CFs between the GCMs, as the 90th and 10th percentile values differ considerably from the average factors. Also, it should be noted here that for some areas a decrease in the intensity of extreme precipitation (CF < 1) is projected by a few models.

4 Risk assessment of climate extremes

4.1 Framework for integrated risk assessment

The economic and human consequences of pluvial flooding in urban areas are often large and diverse, as their occurrences are not easily predictable in due time, and because comprehensive statistics on their impacts are not readily available due to the inherently low frequencies of such events. Also, the large degree of heterogeneity within cities means that a variety of assets are exposed to flooding. Integrated assessment frameworks assist in providing directions for how information about the climate system can be linked to physical impacts and related costs to support decision-makers in planning for and adapting to current and future climatic conditions. Climate model projections, downscaling methods, physical impact models, damage measures and economic valuation are central elements in adapting a holistic approach to address the complexity of integrated risk assessments of pluvial flooding (Figure 4-1).

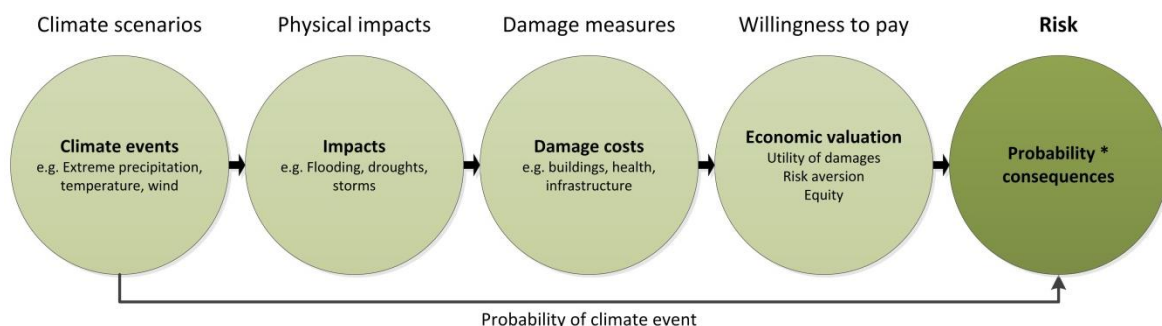


Figure 4-1. Generic structure for climate change risk assessment (publication IV, Fig. 1, and publication V, Fig. 1).

Frameworks for localized risk assessments are often structured based on the main modelling tools, data and assumptions, which are useful in the context of decision-making for climate adaptation in an

urban setting. As climate change occurs over long periods of time, it should facilitate long-term climate change risk analysis covering a ten to fifty year time frame and beyond, with the aim of supporting decision-making on local climate change adaptation, for example, for urban areas. Risk assessments require an integrated approach where various sector-specific in-depth models, such as climate models, hydrological models, agricultural models and different cost and social impact assessment tools, are combined with geographical information on land-use and behaviour to identify vulnerable and risk-prone assets. On this basis, an integrated framework and tool (Danish Integrated Assessment System – DIAS, publication V, Fig. 2) is developed to highlight key uncertainties and to address the complex linkages between the different kinds of data required in a climate adaptation context. DIAS aims at facilitating modelling groups and experts in sharing outputs and data, given the understanding that the multidisciplinary character of risk and adaptation studies demands such a structured approach to collaboration. It is emphasized that using highly detailed geographical data enables the risk assessment to focus on localized impacts for specific assets rather than on aggregated impacts, where uncertainties related to the different modelling components are concealed. See section 2.2 in publication V for detailed information on the DIAS.

4.2 Damage cost assessment

Damage costs can be estimated using a bottom-up approach, where cost parameters are assigned to different assets that are expected to be at risk from pluvial flooding. The assets examined in an urban setting include buildings, historical/cultural values, health, transport infrastructure and bodies of water. The costs associated with damage to these assets can subsequently be transformed into a measure of 'willingness-to-pay' (WTP) reflecting welfare loss, where risk aversion, equity concerns (given by alternative discount rates) and inequality (primarily for LDCs) are taken into consideration.

In the current study (results presented in sections 5.2.1 and 5.2.2), total and annualized damage costs are estimated by combining flood-hazard maps with information on the geographical location of vulnerable assets and individual unit costs for each asset. The damage cost assessment is based on two alternative damage functions that describe the relationship between damage costs for individual assets, surface water depth and precipitation intensity (Figure 4-2). In a traditional "damage curve" (DC) approach, the modelled maximum flood depth during precipitation is used directly as a measure of severity. Using this method, asset damage costs increase linearly with surface water depth until it reaches a predefined level where it is assumed that the maximum possible damage occurs. The water level for maximum damage varies between different assets as a consequence of differences in vulnerability to the impacts of flooding (publication IV, table A1) (Davis and Skaggs, 1992; Jongman et al., 2012). In the 'event-driven' (ED) approach, unit damage costs are kept constant for all water levels exceeding a certain water depth threshold. As assets have different susceptibilities to the water level required to cause damage, a water depth threshold is defined for each asset type that remains constant for all precipitation events. Instead damage unit costs follow the intensity and total amount of precipitation (red ED line and red x-axis in Figure 4-2) (publication IV, table A2). The logic behind this approach is that the likelihood of assets being flooded with water levels above the defined threshold increases with the intensity of precipitation, causing a higher damage cost per flooded asset. This relationship (ED) has been confirmed by the available data for insurance claims from flooding during extreme precipitation in Denmark from 2006 to 2013, where average insurance claims are observed to be three to ten times higher for damage from very extreme precipitation as compared to more frequent (less intense) events (Danish Insurance Association (DIA), 2015). A variety of alternative and more detailed damage functions can also be applied to describe the relationship between damage unit costs and flood severity, including non-linear functions (concave/convex) and threshold (TH)-based methods (Figure 4-2).

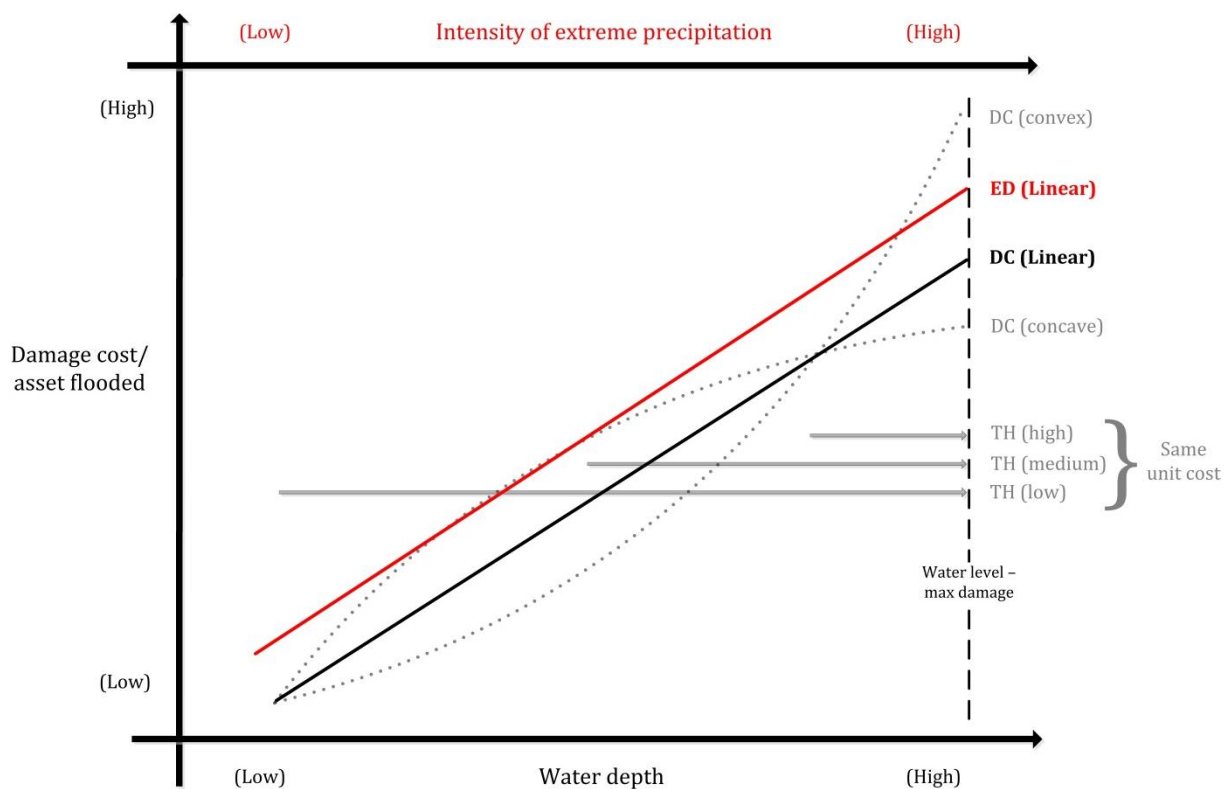


Figure 4-2. Different conceptual damage functions based on flood depth and precipitation intensity. ED = event driven (top x-axis), DC = damage curve (low x-axis), TH = threshold (low x-axis) (figure not included in any of the publications).

4.3 Uncertainties in climate scenarios, impact analysis and economics

Combining projections of climate extremes with analytical tools such as flood models and cost-benefit analysis in a climate adaptation decision-making context introduces high levels of uncertainty. This uncertainty is caused primarily by the inability to accurately project future extreme precipitation and related flood levels, as well as to the methodological shortcomings involved in assessing damage costs for cities over long periods of time. Also, no single recommendation on the use of discount rate, risk aversion factor and inequality factor exists for risk estimates in a climate change context, which provides the basis for great variation in risk estimates, and thus a large degree of uncertainty in the appropriate response (level of optimal adaptation) to future climate change.

The uncertainties related to the different steps of an integrated risk assessment have different characteristics depending on their origin. Structural uncertainties reflect incomplete understanding of the processes and components of the earth system as represented in climate and impact models (Mastrandrea et al., 2010), while other uncertainties are related to economic models in which valuation issues, risk attitudes and discounting approaches can play a major role (publication IV). Precipitation projections are in general very uncertain and predominantly in the short-term model variation, and "noise" from natural variability is a key driver of uncertainty, while the influence of climate scenario becomes increasingly important in the long-term perspective (Hawkins and Sutton, 2011). The downscaling of the frequencies and intensities of extreme precipitation to relevant geographical scales – that is, for specific urban areas – adds yet another large element of uncertainty. Against this background, it can be said that risk assessments of pluvial flooding in cities face large uncertainties simply because it is very difficult to estimate the probability of current and (especially) future events for specific locations. The probability of extreme precipitation may be expressed in the form of a probability density function (pdf), which provides a comprehensive description of precipitation characteristics with respect to both frequency and intensity. In practice, however, it is far from trivial to construct such a pdf, and in some cases more stylized shapes of pdfs are therefore used to explore the

tails of the distribution given certain assumptions about uncertainties (Figure 4-3). In this idealized example, both distributions depict a nearly identical central value of an increase in, for example, daily mean precipitation, which could be interpreted as the mean (median) of the different climate model projections, whereas the tails of the pdfs express (extreme) values further and further away from the mean. The tails of the two pdfs differ significantly in their 'fatness', and while the 'thin-tailed' pdf is heavily centred and symmetric around the mean, the red 'fat-tailed' pdf is somewhat skewed and lends higher probability to extremes. This implies that the tails corresponding to high-end climate scenarios are similarly likely to be relatively 'fat'.

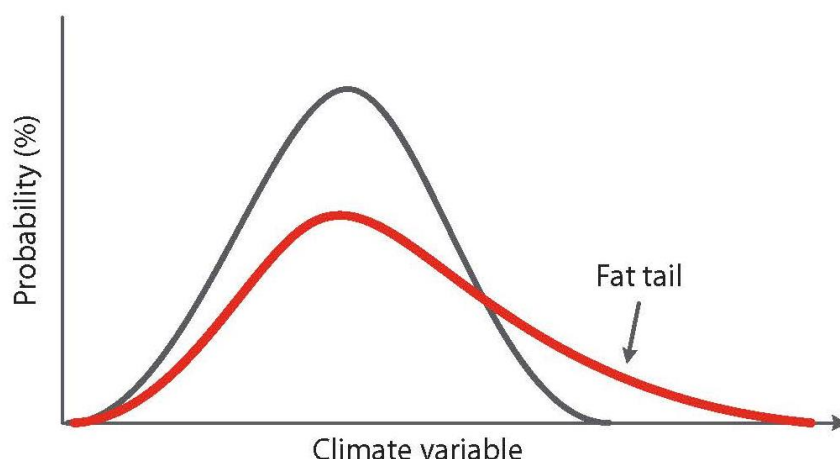


Figure 4-3. Stylized representation of two alternative climate variable distributions (publication IV, Fig. 2).

When assessing the risks of extreme events it is important to recognize that the willingness to pay (WTP) for avoiding the impacts is very dependent on the general risk aversion of decision-makers and society as a whole. One way to include the uncertainty in economic valuation is to apply a risk aversion factor. Risk aversion, by definition, is the reluctance of a person to accept a bargain with an uncertain payoff rather than a bargain with a certain payoff. As already pointed out, extreme consequences of, for example, high-end climate scenarios are by their very nature uncertain. Adding a risk aversion factor to reflect people's attitudes towards risk will increase the estimated damage costs. To exemplify how climate change uncertainties and economic assumptions influence risk levels, we apply the methodological framework to assess flood damage and risks due to extreme precipitation in the city of Odense (sections 5.2.1 and 5.2.2) and through a case study of extreme storms in Cambodia (section 5.2.3). A detailed description of the case study for Odense is found in publications IV (sensitivity analysis) and V (flood risk assessment), while the example from Cambodia is presented in publication VI.

5 Results

5.1 Impacts of urban development and climate change on pluvial flooding

The findings of the combined remote-sensing and flood-model analyses show a clear pattern of increased flooding for precipitation with longer return periods and for events simulated with elevated levels of imperviousness, which is caused by urban development during 1984-2014 (Figure 5-1). Also, climate change is found to dramatically exaggerate flooding for all return periods under both the RCP 4.5 and RCP 8.5 scenario, with the latter having a greater impact in general. The uncertainties related to the projection of future precipitation intensities are found to be large compared to that of urban development, and in all cases we observe that the uncertainty increases with the intensity of precipitation (wider errors bars for RCP 4.5 and RCP 8.5 and when moving towards the most extreme events) (Figure 5-1). There is some difference in how severely the cities are impacted by flooding depending on their geographical location, climatic conditions, soil properties and topographies. For

Odense the share of total area experiencing flooding approximates to 5% for the most severe events while approaching 10% for Vienna and Strasbourg and 20% for Nice.

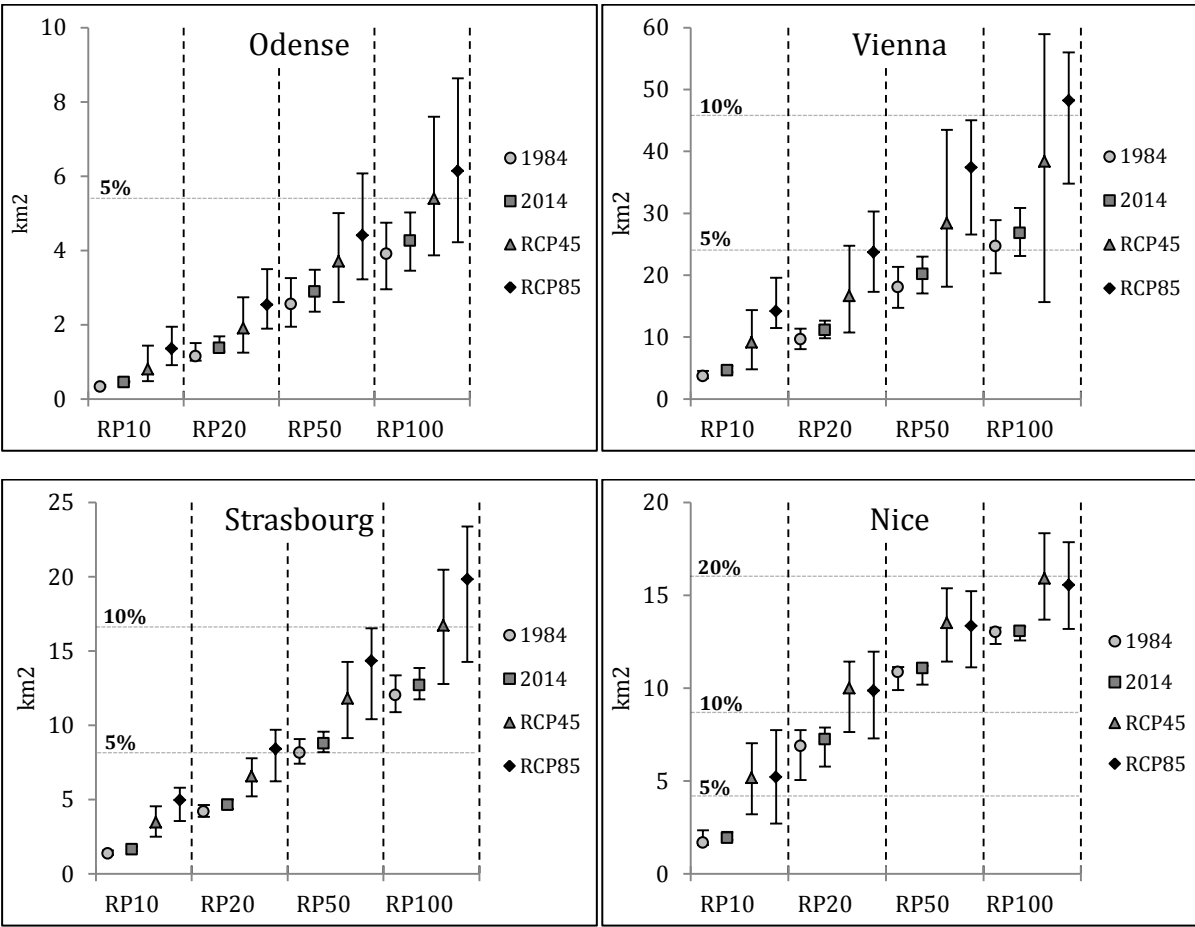


Figure 5-1. Total area flooded by more than 10 cm of surface water during extreme precipitation with different return periods (RP10-RP100). 1984 = imperviousness in 1984, 2014 = imperviousness in 2014. Error bars represent low/high infiltration rates and low/high climate factors (CFs) respectively (low CF = 10th percentile, high CF = 90th percentile). The horizontal %-lines highlight the share of the total urban area for each city (publication III, Fig. 6).

The relative change in flooding as a consequence of urban development is consistent with the conceptual relationship (see section 3.2 and publication III) between changes in imperviousness and overall exposure to flooding, and the impacts of increasing IS fractions are thus found to be inversely related to the intensity of the precipitation (Figure 5-2). This implies that soil-sealing is a key driver of exposure to flooding for the least extreme events (<RP10-RP20), while only marginally affecting flooding during precipitation with longer return periods. Also, we find that the influence of urban development is highly dependent upon the local soil-infiltration properties and that the impact of soil-sealing in this respect follows the soil-infiltration rate. As a consequence, urban development is a main driver of changes to exposure to flooding for Odense and Vienna but only marginally important for Strasbourg and Nice (Figure 5-2). This is in accordance with what was expected from the variations in soil-infiltration properties between the cities, assuming equal historical urban development patterns during 1984-2014 (Table 3-1). For Odense and Vienna the influence of recent urbanisation is comparable with that of the RCP 4.5 scenario, while climate change is the dominant driver of changes for both Strasbourg and Nice. Since we did not observe a high level of variability in the estimated changes in IS fractions during 1984-2014 for the four cities (absolute change of 6%-12%), the importance of this for our results is limited compared to the influence of variations in soil-infiltration rates. A large degree of uncertainty in the impact of climate change is identified, especially for the most extreme events, with a few models projecting a decrease in precipitation intensities and general exposure to flooding for Vienna and Odense (error bars below 0 for RP20-RP100 under RCP 4.5).

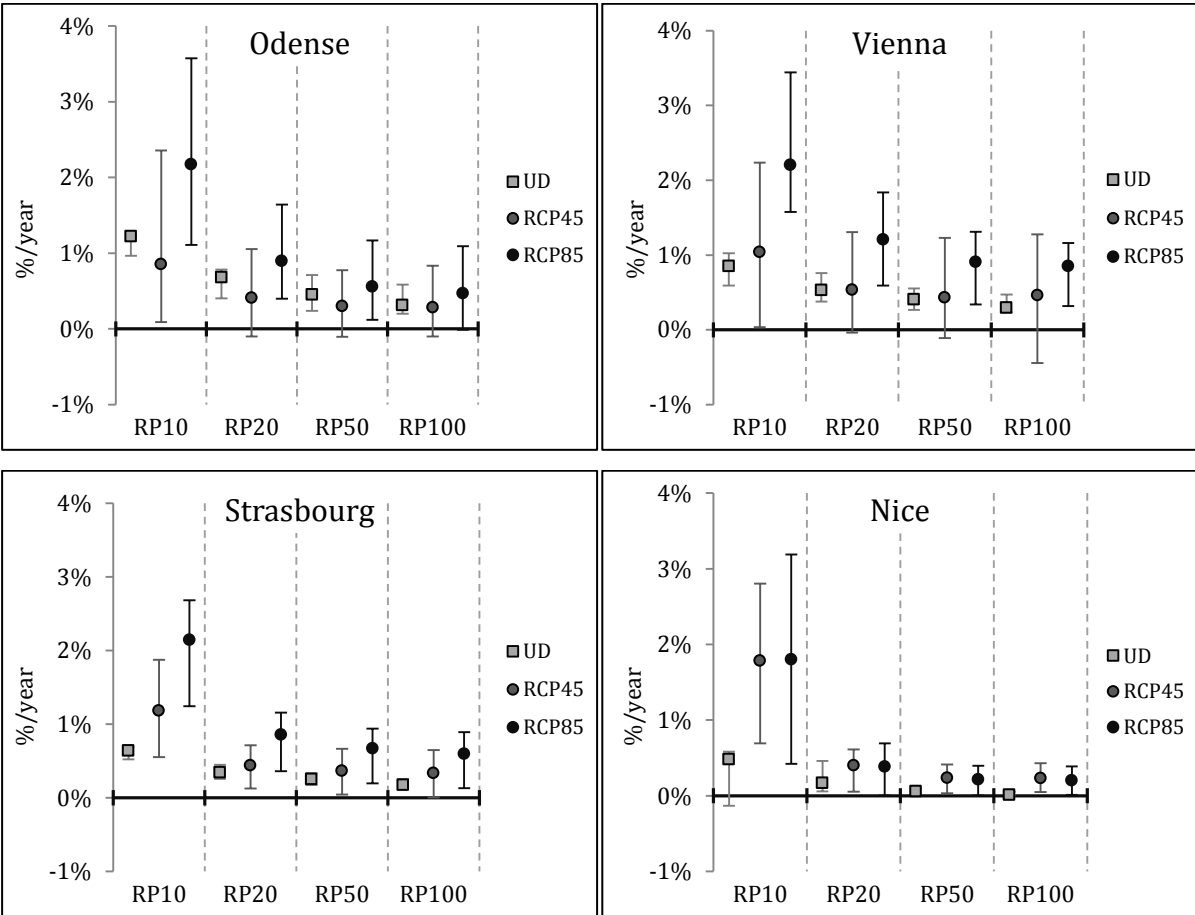


Figure 5-2. Relative annual change in flooded area (>10 cm water depth) due to urban development (UD) and climate change (RCP 4.5 and RCP 8.5) during extreme precipitation with different return periods (RP10-RP100). Error bars represent low/high infiltration rates and low/high climate factors (CFs) respectively (low CF = 10th percentile, high CF = 90th percentile) (publication III, Fig. 8).

The observed impacts of urban development in exposing cities to pluvial flooding are highly sensitive towards the choice of case cities, the historical period selected for analysis of IS changes and the selected flood threshold (flooding is defined as areas with > 10 cm of surface water during precipitation). To overcome the issue that the results are primarily descriptive for the selected cities under the predefined conditions (1984-2014), and to test the sensitivity of the selected flood threshold (which is often defined as the surface water depth where damage begins to occur), the influence of urban development on flood exposure is calculated as an increase in flooding per IS change and investigated for four different flood depth thresholds (representing when an area is considered flooded), ranging from 1-20cm (publication III, Fig. 9). The results of the sensitivity analysis can be merged into the following important findings. Firstly we find that the effect of urban development causes flooding to increase by 0-5% every time average imperviousness increases by 1%, and that flooding is affected more for higher thresholds (20 cm) than for low flood depths. Secondly, we observe that the influence decreases rapidly for all flood thresholds as we move towards the most extreme precipitation events, and that the relative importance of urban development and climate change respectively is unaffected by variations in flood thresholds.

5.2 Risk assessments

5.2.1 Flood risk assessment for the city of Odense

A case study of pluvial flooding in the city of Odense is conducted, following the generic structure for climate change risk assessments (Figure 4-1) and the analytical flow in the DIAS (publication V). The aim of this example is to highlight how detailed spatial analysis can assist in identifying and reducing

key uncertainties in order to provide optimal decision-making support for climate adaptation and in planning the climate-proofing of cities in the future.

Odense is the third largest city in Denmark and has a population of around 170,000 people. Previous flooding events in Odense in the period 2006-2012 have shown that a wide diversity of assets are at risk during extreme precipitation, including transport infrastructure, buildings, human health, aquatic environments, recreational areas and historical and cultural sites. The flood risk assessment is conducted by linking information on the geographical location and properties of relevant assets with flood-hazard maps for extreme precipitation with different return periods. Flood-hazard mapping is done using a combined drainage system and overland flow model (1D/2D model), which calculates surface and sub-surface flows during extreme precipitation. Within this modelling framework, the occurrences of five different design precipitation events, corresponding to return periods of 5, 10, 20, 50 and 100 years under current and future climatic conditions, are simulated for the city of Odense (Municipality of Odense, 2014). The impacts of climate change are investigated for three different climate scenarios, i.e. RCP 4.5, RCP 8.5 and a +6 °C scenario (van der Linden and Mitchell, 2009; Arnbjerg-Nielsen et al., 2015; Christensen et al., 2015).

Surface flooding occurs during all of the examined events, and the total quantity of assets affected by flooding is found to increase with the intensity of precipitation (publication V, Table 2). As an example, the total number of houses affected by flooding ranges from 87 to 576 for the least and most severe events respectively, and similar trends are observed for other building types and for transport infrastructure. In the case of health impacts and irreplaceable assets such as historical buildings, a particularly high number of incidents is seen to appear for precipitation exceeding a threshold of 30 mm h⁻¹ (RP20 – present-day climate). The damage costs caused by pluvial flooding are found to increase with the intensity of precipitation and the extent of flooding, varying from ≈17M€ for the smallest event to ≈320M€ for the event with the highest maximum intensity (Figure 5-3a). The development of total damage costs when one moves from low to high intensity events is not linearly related to the maximum intensity of the individual events: large increases in damage costs are observed when moving from precipitation events of 25mm/hr (RP10 – present-day) to 30mm/hr (RP20 – present-day) and beyond. In a climate adaptation context it is therefore especially important to consider whether the probabilities of these events are expected to increase dramatically in future climate scenarios. The damage to service and industry, houses, multi-storey residential buildings and roads is responsible for a greater share of the total damage costs for all precipitation events (Figure 5-3b). Conversely, damage to bodies of water, leisure facilities, railways and health costs are only marginally present in the cost summary. The absolute damage costs are considered conservative, as some indirect and intangible losses, including disruption to economic activities, traffic delays and impacts on urban ecosystems, are not covered in the assessment.

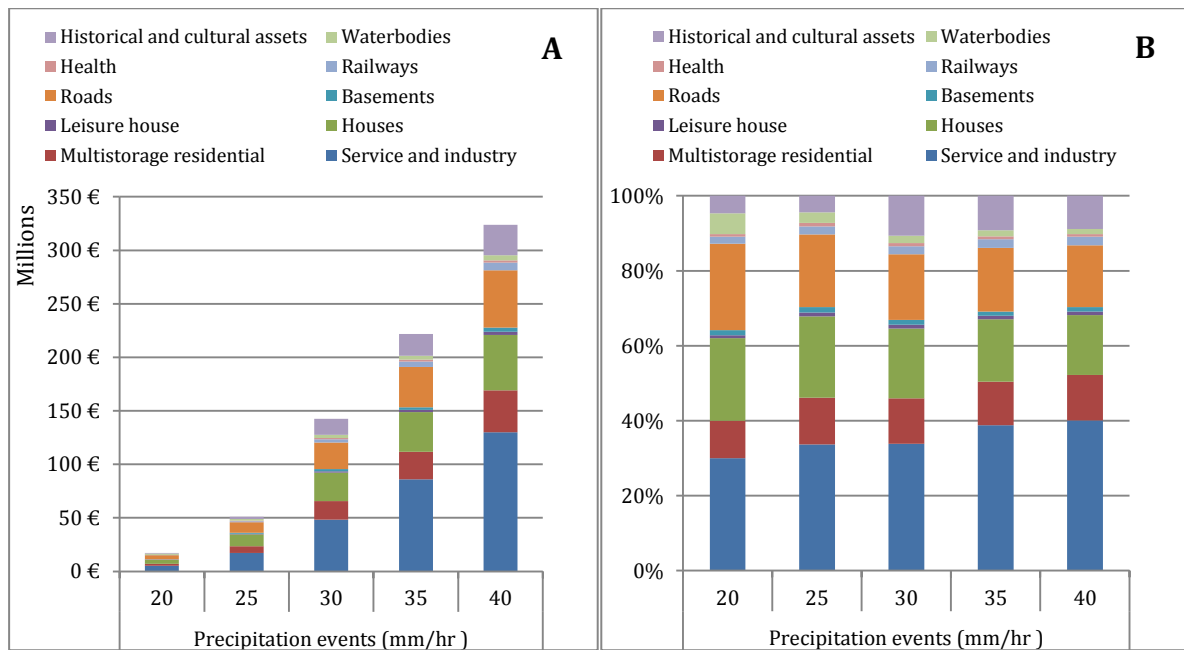


Figure 5-3. Damage cost summary: (a) total costs and (b) share of total cost of flooding in the Municipality of Odense during extreme precipitation with different intensities (costs are measured as the total loss of an event) (publication V, Fig. 8).

The risks of pluvial flooding can be calculated as the expected annual damage cost during a predefined time period by combining climate projections and economic assumptions such as discount rates and risk-aversion factors. From a decision-maker's point of view, this implies that the expected annual risks provide the upper boundary for what society should be willing to pay to protect itself against the impacts of a given extreme event. The level of expected risks, and thus the resources considered appropriate for climate adaptation, depends considerably on expectations of future precipitation extremes. The probability of extreme precipitation is found to increase for scenarios associated with higher changes in global mean temperature (Figure 5-4a). This implies that, if we consider the frequency of specific events, then the distributions derived from the higher-end scenarios are effectively "fat-tailed" as compared to the "thin-tailed" distributions derived from lower scenarios or present-day conditions. As the annual probability of extreme precipitation varies dramatically between the different climate scenarios, the "choice" of climatic future has important implications for the outcome of the risk assessment, and thus for the appropriate response (the optimal level of adaptation) to climate change in this respect. The risks, measured as the probability of precipitation events multiplied by the damage costs, are shown for the alternative climate scenarios, and the costs are calculated as the total costs of an event transformed into to Net Present Values (NPV) over a hundred-year period using a 3% discount rate (Figure 5-4b).

For all climate scenarios, the risks of flooding from extreme precipitation are maximised at precipitation intensities of 30mm/hr (RP20), and we observe annual damage costs ranging from 2-10 M € for the different climate scenarios (Figure 5-4b). For the high-end scenarios (RCP 8.5 and +6°C), risks almost remain constant when moving towards the most extreme events, while decreasing considerably for present-day climate and RCP 4.5. This could suggest that if high-end climate scenarios are expected, climate change adaptation should aim, from an economic point of view, at a high level of protection (40mm/hr), while a more modest level of adaptation may be optimal under present-day climatic conditions and for lower climate scenarios. Also, the large difference in risks between the different scenarios (a factor of 5, 2-10 M €) should be noted, as it highlights a large variation in how much society should be willing to spend on adaptation measures depending on which climate scenario is realised.

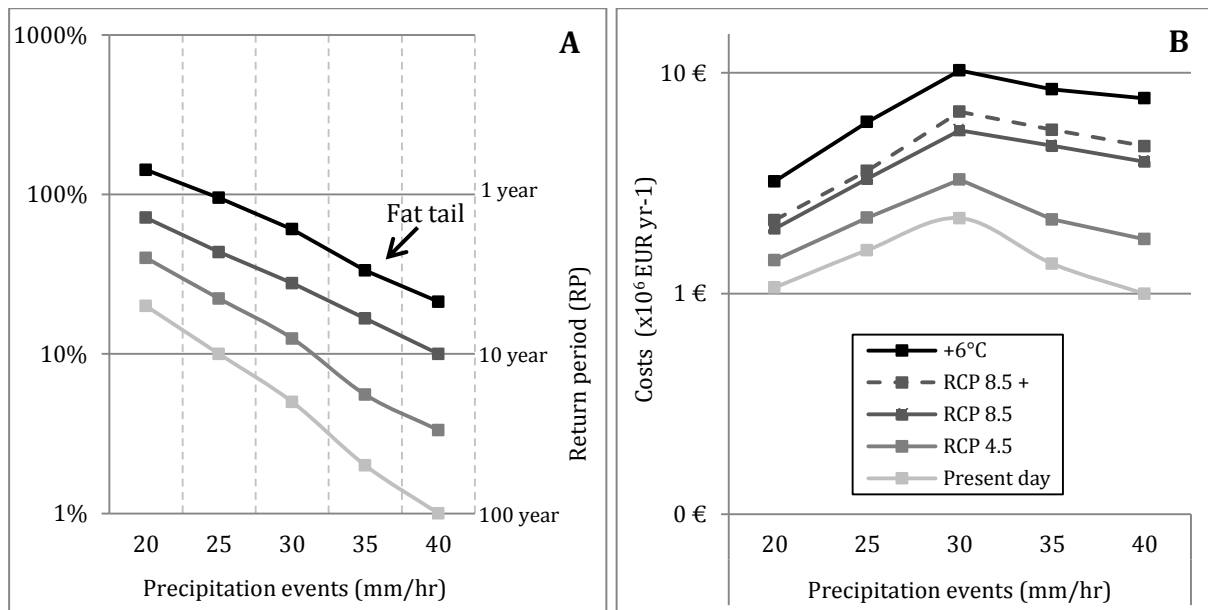


Figure 5-4. (A) Annual probability of extreme precipitation events. 25mm/hr corresponds to a 10-year return period under present-day conditions (10%/year) etc. (B) Risks of flood damage over a 100-year period for different climate change scenarios based on the ED approach, using a 3% discount rate and a low risk-aversion factor of 1, RCP 8.5+ = RCP 8.5 where the value of historical/cultural assets is multiplied by three (publication V, Fig. 7, Fig. 10).

5.2.2 Sensitivity analysis

The assessment of risk from high-end climate scenarios and the impacts of pluvial flooding depend on a number of critical assumptions and methodological challenges related to key uncertainties in climate scenarios and modelling, impact analysis and economics (Halsnæs et al., 2015 - publication IV). Applying alternative economic assumptions to the damage cost assessment expands the range of risk estimates for the different climate scenarios. A sensitivity analysis addresses 32 combinations of climate scenarios, damage cost-curve approaches and economic assumptions, including risk aversion and equity considerations represented by discount rates, to illustrate the role of uncertainties and the importance of key drivers in determining the risk from pluvial flooding. Four different climate scenarios are considered: a reference case reflecting present-day climatic conditions, a 2°C and a 4°C scenario corresponding to the RCP 4.5 and RCP 8.5 scenarios respectively (IPCC 2013), and finally a special +6°C climate scenario provided by the Danish Meteorological Institute (Christensen et al., 2015). The climate scenarios are combined with two different damage assessment approaches (Damage Curve or DC and Event Driven or ED). We then apply risk-aversion factors of 3 and 1 respectively, where a factor of 1 implies risk neutrality that is, cost estimates are not adjusted by the risk perception. The factor of 3 represents a "middle-of-the-road" perspective often favoured by real-life decision-makers, effectively "averaging" risks across a range of different assets, replaceable as well as irreplaceable. Finally, the alternatives are translated into annualized costs using a (moderate) 3% or a (low) 1% discount rate for a total of 32 combinations (publication IV, Fig. 3).

The annualized damage costs for the lowest and the highest risk estimates vary from about 85 million EUR down to less than 1 million EUR (Figure 5-5a). The wide range of risk estimates is a result of different combinations of climate scenarios and economic assumptions, and here it is clear that going beyond a 2°C climate scenario has great implications for the risk estimates. In terms of decision-making, however, it is important to note that most of the combinations of economic assumptions and climate scenarios assess the risk to be between 7 and 30 million EUR yr⁻¹, while only 4 out of the 32 combinations really stand out and go far beyond a 30 million EUR yr⁻¹ risk level. The high-risk cases correspond exclusively to the RCP 8.5 and +6°C climate scenarios, a risk-aversion factor of 3 and a low discount rate of 1%. In conclusion, it can be said that the alternative climate scenarios included in

Figure 5-5a show variation in the risk estimates from ~25 million EUR yr⁻¹ as the highest estimate for the 2°C scenario to about 80 million EUR yr⁻¹ for the 6°C scenario. Keeping the 6°C scenario constant and then alternatively varying the economic assumptions on risk aversion and discount rate provides an almost similar range of risk estimates (Figure 5-5b). Thus, given our assumptions, we can conclude that the climate scenarios and economic assumptions influence the risk estimates in very similar ways.

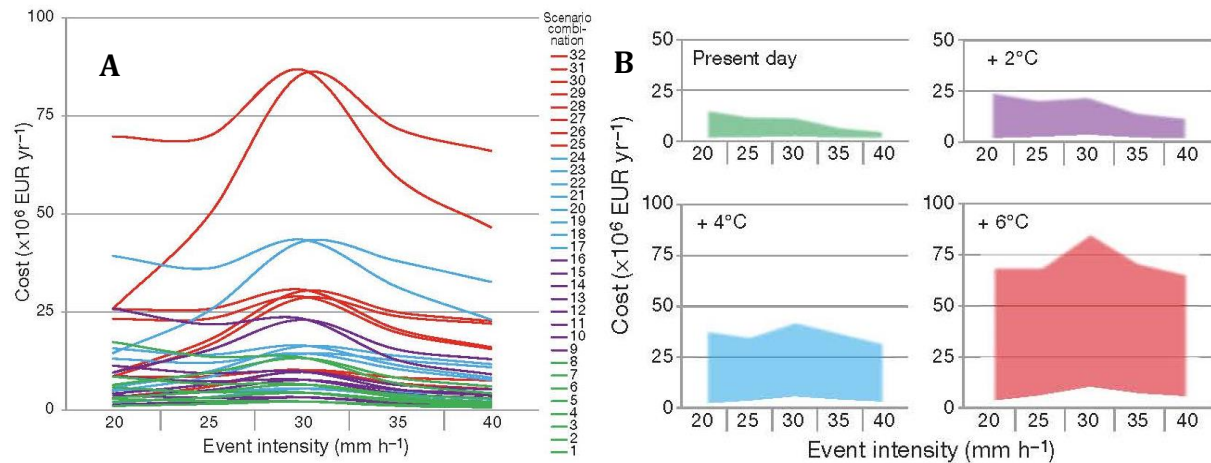


Figure 5-5. (A) Risks represented by levelized costs over a hundred-year period calculated for all 32 scenario combinations. (B) Range of levelized costs for different climate scenarios and precipitation intensities. Red: +6°, blue: +4°, purple: +2°C climate scenario combinations; green = present-day (publication IV, Figs. 9 and 10).

5.2.3 A least developed country perspective: a case study from Cambodia

Least developed countries (LDCs) are particularly vulnerable to the impacts of climate extremes due to their low incomes, weak infrastructure and public institutions, and thus a low capacity for coping with the adverse impacts of climate change. Risk assessments for LDCs are often characterized by even greater uncertainties due to data limitations and because research efforts on future climate extremes and related impacts are not as readily available when compared to highly developed regions. However, despite these uncertainties and limitations, it is extremely relevant to study the consequences of climate change and extreme events for LDCs, as their impacts are expected to be most pronounced here (Field et al., 2012). A methodological framework for estimating damage costs and risks is described and applied to a case study of risks from storms in Cambodia with the aim of highlighting the importance of key uncertainties and specific vulnerabilities when conducting risk assessments for a developing country. A sensitivity analysis is presented in which a few general assumptions concerning trends in climate extremes (climate scenarios) and associated damage illustrates how climate projections, inequality concerns (impacts on low-income household), risk aversion and discount rates influence damage costs and risk estimates considerably. Damage from climate extremes in LDC will in many cases particularly harm people with low incomes. We therefore suggest applying an income inequality factor to the damage estimates to reflect the fact that damage to low-income households should have a high priority.

Two alternative climate scenarios are used to project damage from storms and cyclones in Cambodia during 2015–2030 (Figure 5-6). Climate Scenario 1 represents a continuation of present-day climate and assumes constant frequency of the severe storms corresponding to the mean value of the events for the period 1996–2014. Climate Scenario 2 projects an increased frequency corresponding to a linear extension of the trends observed in the period 1996–2014. The importance of risk aversion is examined by applying a risk-aversion factor of 3 and an alternative factor of 1, which represents risk neutrality. Inequality concerns are included using two different inequality factors (low and high) to represent damage affecting low-income groups. Likewise, two different discount rates (5% and 7%) are included to investigate the effect of alternative equity assumptions.

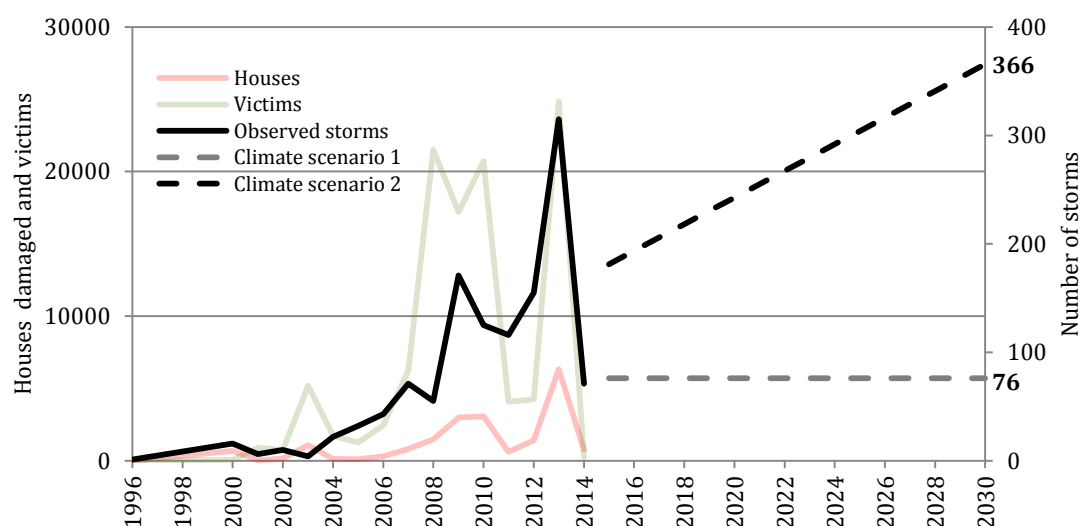
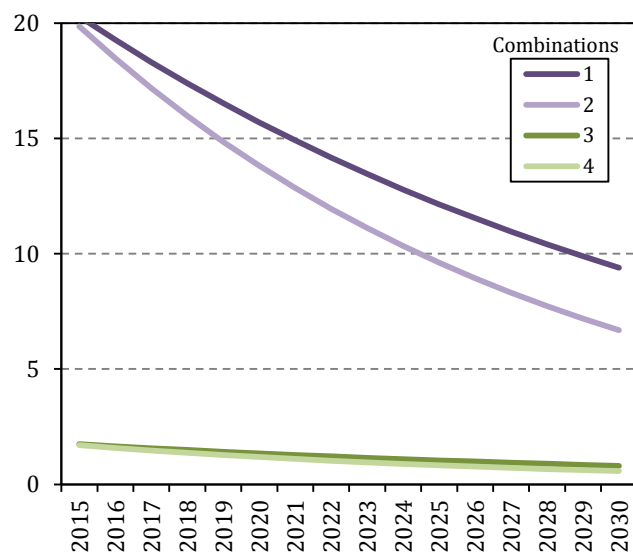


Figure 5-6. Number of damaged houses, victims and observed storms in Cambodia in the period 1996–2014, and projected number of storms in climate scenarios 1 and 2 for the period 2015–2030 (publication VI, Figs. 5.3, 5.4).

A sensitivity analysis combines the climate scenarios, risk-aversion factors and inequality aversion factors to illustrate how risk estimates are influenced by priorities to avoid damage affecting low-income groups in developing countries. The estimates of WTP are calculated for a sixteen-year time frame, which means that we are calculating a proxy value of damage based on climate scenario assumptions for the period 2015–2030 (Figure 5-7). The damage proxy for severe storms increases considerably with the application of income inequality factors. This is the case for both factors, and it can be observed that adding a dimension in which the vulnerabilities of low-income groups are valued as a particularly high welfare loss can make a big difference to economic estimates of what society should be willing to pay to avoid extreme climate events. Adding a risk-aversion factor of three also increases the damage proxies considerably. Finally, in all cases we find a dramatic increase in damage with climate scenario 2 as compared to climate scenario 1, as the number of storms increases here due to climate change. The importance of the choice of discount rate in the NPV calculations is illustrated in Figure 5-7, where combinations of the climate scenarios and the WTP assumptions are calculated as annual NPVs using two different discount rates (5% and 7%). Here it can be seen that the application of high factors of income inequality and risk aversion make a much greater difference to the damage cost proxies as compared to using alternative discount rates. In conclusion, it can be said that the sensitivity cases demonstrate that assessments of welfare implications of extreme events strongly depend on how particularly vulnerable people (e.g. low-income households) are addressed in the risk assessment. It must be remembered that low-income households most often live in houses which are poorly protected against storms, and possibly in geographical areas that are especially exposed to the occurrence of and impacts of extremes. Following these arguments, applying an evaluation framework for assessing the WTP for avoiding damage as suggested in this chapter suggests that, seen from a welfare economic point of view, society should give a high priority to adaptation investments in vulnerable LDCs with a high density of low-income households.



Combinations →	1	2	3	4
Climate scenario	2.48	2.48	1	1
damage proxy				
Discount rate	5%	7%	5%	7%
Risk aversion factor	3	3	1	1
Inequality factor	3.98	3.98	1.83	1.83

Figure 5-7. Index of the annual NPVs of damage cost proxies for different combinations of assumptions with regards to climate scenario, discount rate, inequality factor and risk aversion (publication VI, Fig. 5-6).

6 Discussion

This section presents and discusses the implications of the main findings of this thesis and focuses on highlighting the perspectives for applying and evaluating the developed methodologies and the results in a broader context. The discussion is divided into two parts, corresponding to the main research objectives as listed in the introduction (section 1.2).

Research objective 1

6.1 Impacts of urban development and climate change on pluvial flooding

Most major cities in Europe and globally are characterized by high IS fractions. If present trends towards increased soil-sealing continue, this is expected to aggravate the risk of pluvial flooding further (EU and EEA, 2012). On the other hand, the introduction of more pervious surfaces could count as an adaptation to climate change. Increased knowledge of the importance of both changes to urban land cover and climate change for the exposure of urban areas to flooding will provide substantial insights for planning the climate-proofing of cities in the future, as well as for predicting future changes in flood regimes (Hall et al., 2014). Also, detailed geographical information on the relative importance of urban development and climate change will assist decision-makers and city planners in prioritize resources efficiently between different adaptation measures and mitigation efforts. In this research, we demonstrate the applicability of a combined remote-sensing and flood-model methodology for investigating spatial and temporal variations in the exposure of cities to pluvial flooding due to changes in urban land cover (imperviousness) and climate change. Whereas similar modelling work is carried out for most European cities, often using flood models of much higher complexity for the purposes of, for example, urban drainage design and cloudburst management, the analytical framework presented here is particularly suited for large-scale mapping (i.e. at the city level). The combination of remote-sensing estimates with an easily customizable flood-modelling approach principally allows for analyses that take into account past and present-day urban development (and potentially projected future changes) as well as climate change in a consistent manner that is readily applicable to the majority of cities in Europe and for a predominant proportion of urban areas globally. Arguably, this may prove an important tool for policy-makers in facilitating urban adaptation to climate change at the European level, and is in line with the main outcome of the Paris Agreement (COP21), which places adaptation, resilience and response to the impacts of climate extremes at the core of the continued work of the international community in climate change research and decision-making (EU and EEA, 2012).

The impacts of urban development on exposure to flooding are found to vary considerably between geographical locations and for extreme precipitation with different return periods. Soil texture characteristics and urban topographies are the primary factors determining soil-infiltration rates, and consequently the impact of soil-sealing on run-off volumes and exposure to flooding. Changing levels of imperviousness play a major role in determining the extent and depth of flooding for areas characterized by relatively high infiltration rates, while to a lesser degree affecting urban hydrology for cities with finer soil textures or major differences in elevation. As an example, we find that urban development in Odense and Vienna influenced the extent of flooding considerably, while only marginally affecting it for Strasbourg and Nice. This indicates that green adaptation measures are only an efficient adaptation strategy preventing pluvial flooding for some locations. We observe a declining impact of soil-sealing with increasing precipitation intensities (greater impacts for shorter return periods), leading to the obvious conclusion that using pervious surfaces as adaptation measures are most efficient for the least severe events, while not providing any noticeable protection against flooding during very extreme precipitation. The four selected cities represent a wide range of soil-infiltration rates, and the reported impacts of urban development on flood severity could be expected to be representative for many other cities, particularly in Europe. We have found that an increase in overall imperviousness of 1% causes the area affected by flooding to increase by up to 5% for the shortest return periods, while only slightly affecting flood exposure during very extreme precipitation. From the perspective of climate change adaptation, this clearly demonstrates quantitatively the

effectiveness of pervious surfaces as measures for reducing exposure to flooding. Conceptually, if measures were implemented reducing overall imperviousness by 1%, exposure to flooding would decrease by up to 5% for some locations and only marginally affect flood levels for other locations. Results suggests that the past thirty years of urban development alone has increased exposure to pluvial flooding by 0.5-1.2%/year for RP10, decreasing to 0-0.4%/year for hundred-year events. Corresponding estimates for RCP 4.5 and RCP 8.5 (climate scenarios) are in the order of 1-2%/year (RP10) and 0.2-1%/year (RP100), indicating that the impacts of changes to urban land cover and climate change are comparable and that both adaptation and mitigation efforts are central in reducing the exposure of urban areas to pluvial flooding.

The findings of this study can be used in combination with projections of urban land cover to provide estimates of expected changes in flooding regimes due to future urban development. Assuming that urban development trends continue at their current rates over the next hundred years for Nice, Strasbourg, Vienna and Odense, this implies that the additional share of the total urban land cover which can be expected to experience flooding during extreme precipitation approximates to 0.2–1.1% (the share of urban land cover experiencing flooding at present-day levels of imperviousness ranges between 0.5-15%, but is in most cases below 5-10%; see Figure 5-1). For comparison, climate change is found to cause surface flooding to an additional 0.3–5% of urban land cover and can be expected to be the major driver of changes to pluvial flood regimes for some locations, including cities that have similar characteristics (soil textures, urban development, topography, climate projections) like Strasbourg and Nice. The relative importance of past and future urban development and climate change for overall exposure to flooding will differ according to the city and region-specific urban development patterns. The results presented here are thus not considered valid for regions that are characterized by rapid urbanisation, including some Asian and African megacities. For such regions, urban development will most likely be the primary driver of changes to exposure to pluvial flooding.

The analyses of the impacts of climate change on extreme precipitation suggest that the degree of change is following that of general climate change: that is, as global warming increases, so does the intensity and frequency of extreme precipitation. The uncertainty associated with climate change projections and with different methods of downscaling is well documented, and our results confirm that projections of extreme precipitation differ considerably between different combinations of GCMs and RCMs, and even with some disagreement over the direction of change (i.e. whether events are becoming more or less intense and frequent) (Frei et al., 2006; IPCC, 2014; Sunyer et al., 2014). As a result, the derived climate factors exhibit large variations within the individual climate scenarios. Also, some uncertainty remains in the projected level of change as the estimated change factors are derived using combinations of multiple GCMs with only one RCM. Including a larger number of RCMs would potentially change both the average factors and the calculated percentiles. Adopting a conservative approach, where multiple model runs are used to calculate average change factors, which represents a “middle of the road estimate”, is commonplace. However, if used for adaptation planning, one could instead argue for focusing on the tails of the distributions (best-case and/or worst-case scenarios) to ensure robustness in decision-making.

A few challenges related to the methodology presented here need to be considered when interpreting the findings of the analyses. The flood model used in this study does not include a module for spatial representation of the drainage system. The geographical location of surface flooding may therefore be inaccurate for some locations due to inconsistent dimensioning, since in practice the actual drainage system is not likely to be perfectly dimensioned according to a five-year rainfall event for all locations (the full load of the drainage system is assumed to correspond to a five-year event for all cities). Neglecting the sewage system, errors are also introduced into the extents and locations of flooding, but these effects are assumed to be localized, and their importance decreasing for more extreme precipitation (Paludan et al., 2011). Using a more advanced hydrological model (e.g. 1D/2D models including a drainage system component) reduces the transferability of the overall method to other locations where such data are not readily available. Evidently, the choice of flood model (MIKE 21 overland flow model) makes it easily transferable to other cities at the cost of some precision. Detailed

information on location-specific soil-infiltration rates during extreme precipitation, which is the primary parameter determining the impact of urban development, is often not available, and the uncertainty surrounding the selected values is considered to be very large. To represent some of this uncertainty, we included low/high values, and we expect the actual impacts of soil-sealing to fall within the estimated range of flood responses as calculated here. However, the results should still be interpreted with some caution. Also, the soil water/moisture content at the onset of precipitation can influence the amount of run-off substantially. In the current study, soils are kept dry at the beginning of all simulations to ensure that the results are comparable between the different precipitation events and different geographical locations.

The outputs of the urban development analyses, where an increase in overall IS fractions of 7-12% during 1984-2014 is observed, are considered fairly robust, as the method being applied is well-established and documented, though a few aspects deserve additional attention. Using information on vegetation cover to estimate impervious surfaces is highly sensitive to the presence of bare soil and should be used with caution outside urban areas, as the accuracy decreases considerably for other types of land cover (e.g. agricultural areas, forest etc.). Also, some uncertainty remains due to differences in the spectral response function between the Landsat TM and Landsat OLI sensors, as official conversion factors are not yet available for all locations and environments.

6.2 Remote sensing of impervious surfaces

Satellite imagery and remote-sensing techniques provide almost complete coverage of the past forty years of changes to land cover and land use globally, including in urban areas. However, many of the existing methods based on remote-sensing techniques are often considered highly complex and inaccessible by potential users, in particular outside the scientific community. A simple method for estimating the quantity and location of IS, which is based on the freely available Landsat archive, covering the past thirty to forty years of global urban development, is developed to facilitate the mapping of urban land cover and temporal changes in it for a wide range of people and applications, including flood-modelling. In the current study we develop and apply a method for the spatiotemporal mapping of IS as a proxy for urban land cover by use of simple linear regression models based on vegetation indices from remote sensors. We observe a relatively low variability in accuracies across geographical locations, as well as for urban areas characterized by diverse vegetative and climatic conditions, suggesting that vegetation cover, as measured from Landsat 8 imagery, can be used to provide estimates of IS fractions for a major proportion of urban areas in Europe today, which is sufficiently accurate for a multitude of applications (Figure 6-1b). In combining the findings of this study with the results of previous research efforts conducted on data from earlier Landsat missions (especially Landsat 5 and 7), it is evident that IS can be mapped solely from Landsat imagery at the same level of accuracy for the past thirty to forty years. Consequently, this enables simple and systematic analyses of historical changes in small-scale imperviousness for many cities globally.

The results of the accuracy assessment clearly indicate that potentially local regression models can be "spatially transferred" to quantify IS fractions for other urban areas without losing high levels of accuracy (Figure 6-1a). The VI/IS relationship is found to be similar for cities characterized by comparative vegetative and climatic conditions, and cross-validations of the developed models show equivalent results with relatively low errors for a number of different combinations of city-specific models and urban sub-areas. For this purpose, the Soil Adjusted Vegetation Index (SAVI) is found to perform the best. Compared to other vegetation indices, SAVI reduces the influence of variations in soil background colour/building materials, which arguably could be the cause for the better performance of the models based on SAVI. The results of the analyses for the regional regression models are promising in relation to developing models, which can be applied to multiple cities over a larger geographical area. This also demonstrates that VIs, and especially SAVI, show similar characteristics for cities located in areas with similar vegetative and climatic conditions, and that single regression models based on Landsat VIs (SAVI in particular) can be applied uniformly for multiple urban areas with adequate precision. However, if regional regression models are to be developed and applied consistently, they should be based on a somewhat larger sample as compared to what has

been included in the current study (samples from eight cities are included in this study). The development of such regional models would enable the simple and resource-efficient quantification of small-scale IS fractions accessible to a much wider audience compared to what is currently the case.

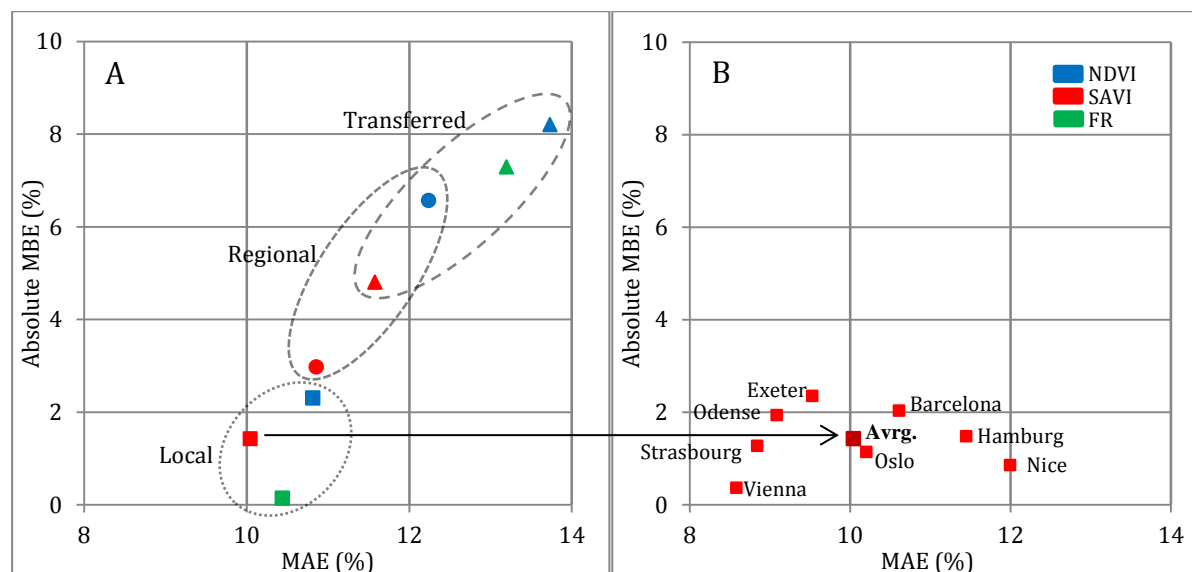


Figure 6-1. (A) Average MAEs and average absolute MBEs for local, regional (European model – SAVI/NDVI data compiled from the sub-areas of all eight cities) and spatially transferred linear regression models. (B) MEAs and absolute MBEs for local linear regression models based on SAVI (figure not included in any of the publications).

There is some evidence of a lower dynamic range in SAVI (and NDVI) for natural vegetation in southern Europe, which may affect accuracies for Nice and Barcelona, indicating that the use of VIs for IS mapping is sensitive to the amount of vegetation and may not be applicable for urban areas located in regions characterized by sparse vegetation cover and larger areas of bare soils. This implies that using information on vegetation cover to monitor urban land may not be appropriate for semi-arid/arid regions (sparse vegetation cover) and for some cities in LDCs, including in Africa and Latin America, where larger proportions of road infrastructure consist of bare soil. Also, shadows from tall buildings and trees covering pervious surfaces reduce the signal as measured by the sensor, consequently reducing the overall accuracy of the models. Visual inspection of the high-resolution images suggests that shadows are not a major feature for most of the urban areas covered in the study, though this may be a major constraint for the application in some mega cities, where high-rise buildings are commonplace.

Research objective 2

6.3 Risk assessment of pluvial flooding

In the present study, we frame the climate change risk assessment in terms of how much society should be willing to invest in adaptation measures based on willingness-to-pay estimates. Seen from the perspective of a climate change adaptation decision-maker, society should be willing to pay adaptation costs that are at least equal to the avoided costs of climate change impacts. It is therefore relevant to compare the costs of adaptation with the risk reductions achieved by different measures, assuming that a given climate scenario is emerging.

An integrated framework for assessing the impacts and risks of climate extremes, focusing predominantly on pluvial flooding, is described to highlight key uncertainties in climate change adaptation decision-making. A sensitivity analysis examines the importance of key variables and methodological challenges related to the main uncertainties in climate change projections, impact assessments and economic assumptions. The assumptions made in any of the analytical steps will

influence the overall results of the risk assessment to a greater or lesser extent, which may have important implications for the responses of decision-makers to climate change. A wide range of risk estimates, resulting from several combinations of climate scenarios and economic assumptions, show that climate change uncertainties and variations in economic assumptions can influence the risk estimates in very similar ways. Using a disaggregated approach can provide decision-makers with knowledge of the importance of different expectations and assumptions concerning climate change and economic valuation for the level of cost-effective adaptation required. In adequately eliciting these uncertainties in an integrated framework, an ensemble of comprehensive model experiments is required that is specifically designed to decompose the variation and to take into account key factors such as the scenario and model uncertainty. This study demonstrates that, when it comes to decision-making, the actual expectations concerning future climate scenarios and the economic assumptions made are very important in determining the risks of extreme climate events, and therefore the level of cost-effective adaptation seen from the society's point of view. This is in opposition to the existence of a single optimal level of adaptation, and it is argued that the estimated risks will always vary according to the priorities of decision-makers, stakeholders and preferably society as a whole.

One way to address the high levels of uncertainty surrounding risk assessments for urban environments is to use a very detailed context-specific data and modelling approach, such as the DIAS (publication V, Fig. 2), which can help to identify particularly vulnerable and valuable assets that it is important to protect through the implementation of climate change adaptation measures. Also, the findings highlight that very rare and historical/cultural values may need special attention in this context in order to influence the overall outcome of a standardized risk assessment. In this way, a precautionary approach in relation to specific assets can be important to consider in relation to adaptation decision-making.

Illustrating the risks of different climate change scenarios, the decision-making issue could be presented using adaptation cost curves for risk reduction (Figure 6-2a). When adaptation costs (black line) are above the risk curve, the benefit of implementing adaptation to protect against a specific event is less than the adaptation costs. The straight line represents a fictive example of an adaptation cost curve and is merely inserted for illustrative purposes. Using this example, society should aim for protecting against flooding during precipitation intensities of 30mm/hr if a +4°C scenario is expected to realize over the next 100 years. In the case of a lower increase in global mean temperature society should instead, from an economic point of view, aim for a lower level of protection. The optimal level of protection under the different scenarios is highlighted in Figure 6-2. The recommended risk management level will of course depend on the exact shape of the adaptation cost curve and the expectations concerning future climate change (society should be willing to invest more on adaptation assuming high-end scenarios are realized), which can be very diverse for different geographical locations. To put the decision-making perspective into a larger context – that is, in terms of climate change mitigation perspectives – the reduction of the risk of urban flooding can also be seen as a measure of the benefits of avoiding the consequences of alternative climate change scenarios. For illustrative purposes, Figure 6-2b shows risk estimates when moving from present-day climate to +2°, +4° and +6°C climate change scenarios. We assume here that the risk-aversion factor applied to the willingness-to-pay estimates increases linearly from 1 to 2 when we are on a trajectory to a 6°C climate scenario. However, one might also argue that the risk-aversion factor will increase with global mean temperature change due to ambiguity in relation to future uncertain high-consequence events (Weitzmann 2011). Confronting the climate change risk estimates with mitigation issues indicates that, by considering different levels of temperature change, the risk function will be convex in shape (solid line), while adding a risk-aversion factor that increases with temperature clearly results in a much faster increase in the risk curve (dashed line). Applying similar assumptions in a global decision-making context thus points to the conclusion that a more ambitious level of climate change mitigation should be implemented.

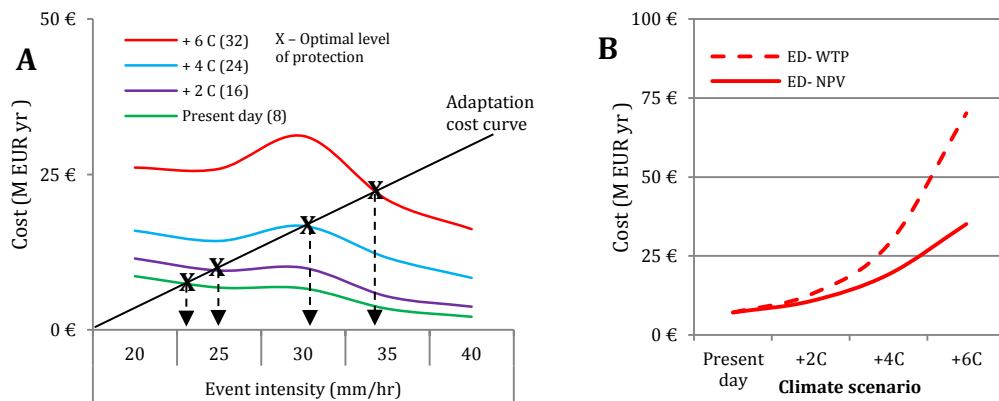


Figure 6-2. (A) Levelized risks for the different climate scenarios and a stylized adaptation cost curve (solid straight line) for risk reduction; numbers in brackets are from the 32 combinations in publication IV, Fig. 3. The optimal levels of adaptation under the different climate scenarios are shown. (B) Levelized costs for different climate scenarios using the event-driven (ED) damage assessment method and a 3% discount rate. The risk aversion factor increases from 1 to 2 as climate change increases in the willingness-to-pay (WTP) measure. NPV: net present values (publication IV, Figs. 12 and 13, adjusted versions).

Another important point to consider in the perspective of decision-making on climate change adaptation is the issue of time and learning: for example, what happens when the focus moves from low-end climate scenarios with possible moderate impacts to higher-end scenarios with more severe impacts. Since decisions about adaptation measures typically have a much shorter time perspective than developments in the climate system, it is important to consider the timing of when risks associated with different climate scenarios may actually materialise and when a given adaptation becomes necessary. One way to incorporate the time perspective is to compare the time frame determined by different climate models of when alternative global mean temperature changes will emerge. Comparing the global annual mean temperature projections for the RCP 8.5 scenario of 38 CMIP5 (Taylor et al. 2012) members compared to the pre-industrial 1881–1910 period, Christensen et al. (2015), for example, showed that around 2100 is the “earliest” time a 6°C global mean temperature change could be achieved. It is important from a decision-making point of view to consider the magnitude and uncertainties of damage estimates when we move from, for example, a 2°C to higher-end scenarios, and timing is important here when it comes to planning adaptation. Recent climate simulations suggest that a 4°C increase could already be achieved around 2050 if current high GHG emission rates continue. Hence, depending on the time frame of the actual adaptation considered, it may be highly relevant, within a time frame of up to 2100, to assess options in the context of risks when moving from a 4°C scenario to a 6°C scenario.

6.4 Risk assessments of climate extremes for least developed countries

Damage from climate extremes in LDCs will in many cases particularly harm people with low incomes. We therefore suggest applying specific assumptions to WTP estimates for avoided damage for LDCs that reflect risk aversion and inequality, giving relatively high weight to damage and thus income losses to poor households (Markandya 1998). A methodological framework, adjusted to overcome the issues of data availability and equity concerns, has been applied to a case study of damage from severe storms in Cambodia to illustrate how assumptions about trends in climate extremes and impacts on low-income groups can be addressed for risk assessment purposes, and how uncertainties in these parameters influence the outcomes of such analyses. A sensitivity analysis in which a few general assumptions about trends in severe storms and inequality, in terms of impacts on low-income households, demonstrates that the application of these specific factors for LDCs strongly influence WTP estimates for avoided damage. Also, we observe that the application of high factors of income inequality and risk aversion make a much greater difference to the damage cost proxies than the use of alternative discount rates of 7% versus 5% (Figure 5-7). In conclusion, it can be said that the results of the sensitivity analysis demonstrate that assessments of the welfare implications of extreme events

in LDCs like Cambodia strongly depend on how vulnerable people and low-income households in particular are treated in the assessments. It must be remembered that low-income households most often live in houses which are poorly protected against storms and that low institutional capacities impeding access to financial aid often hinders the rebuilding of damaged assets in such societies. Applying an evaluation framework to assess the WTP for avoiding damages, as suggested here, implies that, seen from an economic welfare point of view, society should give a high priority to adaptation investments in vulnerable areas with a high density of low-income households.

The relatively simplistic climate scenario assumptions do not provide an optimal representation of future climate change and related events in Cambodia, but due to limited data availability, the alternative scenarios are used to illustrate the implications of future increases in the frequency of extreme events for purposes of risk assessment. Damage cost reports for storms and cyclones are not available for Cambodia, and we are therefore using historical trends in the number of damaged houses and victims during severe storms as proxy values for damage costs. Using such proxies rather than actual damage cost data implicitly assumes that the number of incidents represents damage and that the magnitude of damage for individual houses and people is constant over time. Also, it implies that the damage associated with each severe storm is similar for both climate scenarios, and that only the number of houses and victims affected differs between the two projections.

7 Conclusions and perspectives for future research

It is virtually beyond doubt that urban areas will become increasingly exposed to the occurrence and impacts of pluvial flooding due to the joint effects of continued urban development, e.g. causing increased levels of soil-sealing, and climate change, which will further increase the intensity and frequency of extreme precipitation.

The results from the four cities analysed here show that changes to land cover within cities can play a central role in their exposure to flooding and conversely to their ability to adapt to a changed climate. We have identified a clear trend towards a greater impact of soil-sealing for the least severe precipitation events, while only marginally affecting flooding during precipitation with longer return periods. Urban development is found to have a large influence on the exposure to flooding for urban areas characterized by coarse soil textures and limited topography, as soil-infiltration is excessive in these cases, increasing the influence of soil-sealing. Climate change impacts on precipitation extremes are highly uncertain, but with average change factors projecting a significant increase in precipitation intensities for all the cities. The results from our case studies indicate that the influence of urban development in exposing cities to flooding is comparable to what can be expected in the end of this century under the RCP 4.5 scenario, and that the relative importance varies considerably between locations as a consequence of differences in soil infiltration properties and local climate change factors. In all cases we find the expected changes in precipitation intensities under the RCP 8.5 scenario to affect flooding the most. Soil-water infiltration rates during extreme precipitation vary considerably over small distances. However, current knowledge of the factors determining instantaneous local soil infiltration rates is limited, causing higher uncertainties for such estimates. Increased research efforts within this area, including extensive fieldwork, is needed for better understanding the changes in the hydrological responses in urban areas due to increased soil-sealing. Another obvious research continuation that might build on the investigations conducted for this thesis is to analyse the importance of urban development in increasing the risks of pluvial flooding as opposed to examining the exposure as has been done here. The outcome of such analyses would serve to refine our findings directly in a decision-making context i.e. by including comprehensively the economic dimension, which would be particularly useful for decision-makers at all institutional levels. Also, including dynamic projections of urban development and urban land cover in the analyses could contribute considerably to increasing our knowledge on how the susceptibility of cities can be expected to change in terms of both the short- and long-term perspectives.

Our study clearly demonstrates that the remote-sensing and flood-modelling approach used here can be used – and is easily transferable – in terms of quantifying and mapping the dual importance of urban development and climate change for changes in urban flood exposure to other geographical locations both regionally and globally. Continued research into the main drivers affecting overall exposure, vulnerability and risk for cities is required to provide European (and global) decision-makers with adequate knowledge of how to plan pluvial flood-proofing for cities in the future. For many applications, satellite imagery provides superior coverage of urban land cover. The findings of this study show that IS fractions (as a proxy for urban land cover), and spatiotemporal changes to them can be mapped with reasonable accuracy from the 1980s onwards by use of simple linear regression models based on vegetation indices calculated from Landsat medium-resolution imagery. If regional regression models for use in multiple cities over larger geographical areas are to be developed and applied consistently, they must be created from large samples of urban areas covering a considerable share of vegetative and climatic conditions locally, regionally and globally. Future research directions within this area in a context of flood modelling should focus on the exploration of high-resolution imagery for IS mapping as extended time-series become available at lower economic and computational costs in the near future. In this context it could be worthwhile to investigate not only the expected value added by employing such extended high-resolution time series, but also to innovate new methods to allow for an optimal integration of remotely sensed imagery of different resolutions.

Risk assessments for flooding in local areas are very uncertain, particularly in relation to the downscaled precipitation data, which are commonly the backbone of most studies of urban pluvial flooding. Large uncertainties are inherently related to the projections of extreme precipitation and to risk estimates, including damage cost estimates, discounting and risk aversion. The latter are key issues for real-life decision-makers, that is, how much society should be willing to pay for climate change adaptation, which are often overlooked or drastically simplified in many real-life climate change impact assessments. In this study we address the propagation of uncertainties and test critical assumptions in relation to a particular case study of urban flooding. We demonstrate that, in terms of decision-making, actual expectations concerning future climate scenarios and the economic assumptions adopted are very important in determining the risks of extreme climate events and thus the level of cost-effective adaptation seen from the society's point of view. The actual level of risk associated with flooding from extreme precipitation in Odense is found to vary in near equal parts due to uncertainties in climate projections and economic assumptions. We therefore conclude that climate scenarios and economic assumptions influence risk estimates in very similar ways. Using a risk assessment framework as presented here implies that risk estimates should be considered conservative, as many intangible costs including mental health impacts and biodiversity concerns are not addressed due to limitations in the current methodologies for estimating and quantifying damage to such assets. Further methodological development within this area is sorely needed and will improve risk assessment and contribute with additional knowledge for decision-makers planning for climate adaptation. For example, damage caused by extremes should not be considered constant over time and will most likely decrease with the occurrence of events due to the inherent learning of individuals and society as a whole. Consequently, research with a distinct focus on quantifying the effects of learning could increase the accuracy of risk assessments and provide decision-makers with an improved knowledge base when adapting to climate change.

Least developed countries (LDCs) are particularly vulnerable to the impact of climate change and extreme events due to their low incomes, weak infrastructures and institutions, and low capacity for coping with climate change (IPCC 2014). This implies that damage associated with extreme events is often very serious. To address this issue, we propose the inclusion of an inequality factor, which gives relatively high weight to damage and thus the income losses of poor households. The conclusion is that, if vulnerabilities and inequality concerns are taken into account in adaptation planning for regions with a large share of low-income groups, a strong case is made for allocating economic resources to the protection of least developed countries.

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